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Droplet sampling in cumulus clouds

by

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Summary

An analysis is made of 150 impactions of cloud droplet samples made in cumulus clouds varying in vertical depth from 750 to 7,000 ft.

From a consideration of the spectra (meaned for each cloud) relating droplet number with droplet diameter, a mode diameter of about 8 microns is found. A secondary mode diameter of about 15 microns is in evidence in some clouds and this is considered to be associated with cloud development. Numbers of droplets per $cm.^3$ are in the main between 100 and 300 though extreme values of 19 and 976 occur.

Spectra relating water content with droplet diameter show that in clouds between about 750 and 2,500 ft. thick the bulk of the liquid water is contained in droplets of about 8 microns diameter whereas in clouds between about 4,000 and 7,000 ft. thick the mode diameter is about 18 microns. The highest value of water content found is 4.97 $gm.m^{-3}$.

Evidence is found that mean volume diameter and water content tend to increase with height and that high values of water content are due to larger droplets rather than to greater numbers of droplets per $cm.^3$.

A droplet distribution formula given by Best is examined and the constants involved are found to depend on the largest size of droplet present.

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1. Introduction

On eight days between June and September 1951 ten flights were made in a Hastings aircraft of the Meteorological Research Flight for the purpose of taking samples of cloud droplets in cumulus clouds. In this paper the results of the flights are examined, summarized and compared with the results of other workers.

2. Experimental technique

The method of sampling was similar to that described by Mazur (1) and an account of its use in stratocumulus clouds has been given by Frith (2).

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The aircraft impactor shown in fig.1 contains a slot into which a glass slide can be fitted and a shutter mechanism which can expose the slide for a certain time interval (in this case 1/75th sec.). The impactor was pushed through a hole in the window near the second pilot's seat and, when flying in a suitable cloud, operation of the shutter would expose the slide to the cloud droplets. The slides had previously been coated with a layer of magnesium oxide and the effect of droplets striking this layer was to give rise to small pits. After each flight the slides were microphotographed and a count made of the number of pits with diameters falling within certain specified limits.

It has been estimated(3) that a pit of diameter "a" is due to a droplet of diameter ".713a".

The flights were made in cumulus clouds varying from about 1,000 to 7,000 ft. in vertical extent. In the thicker clouds samples were generally taken at height intervals of 1,000 ft. whereas in the thinner clouds samples were generally taken at intervals of about 100 ft., and several samples were taken at the same height. In all 150 samples were taken during the ten flights.

The camera used to photograph the slides consisted in part of a microscope and a graticule on which were a number of circles of decreasing diameter. These diameters were related by $D = D_0 . 2^{N/2}$ where D is the diameter of the circle and N = 0, 1, 2, 3 etc. From this expression it will be seen that the areas of the circles are in geometric progression of common ratio 2. A photograph of the graticule was superimposed on each droplet sample, the actual diameters of the graticule circles being a function of the focal length of the microscope objective lens. The droplet diameters corresponding with the series of graticule circles were 5.28, 7.48, 10.41, 14.95, 21.39, 29.95, 42.10, 59.90, 84.0 and 119.0 microns after making allowance for the factor 0.713 mentioned above.

The first step in analysing the photographs of the samples of cloud droplets was to count the numbers of droplets of different sizes. The counts were made by assessing the numbers of droplets within categories which, as far as could be judged by eye, had approximately the same diameters as the graticule circles and assuming that the graticule diameters were the mean diameters within those categories. The series of diameters given above should cover the following ranges.

TABLE 1

Size category	Diameter of graticule circle x.713 (microns)	Spread of diameters (microns)	True range within the category (microns)	Mid point of range (microns)
0	0	0-2.64	2.64	1.32
1	5.28	2.64-6.38	3.74	4.51
2	7.48	6.38-8.95	2.57	7.67
3	10.41	8.95-12.68	3.73	10.81
4	14.95	12.68-18.17	5.49	15.43
5	21.39	18.17-25.67	7.50	21.92
6	29.95	25.67-36.02	10.35	30.85
7	42.10	36.02-52.0	15.98	44.01
8	59.9	52.0-72.0	20.00	62.0
9	84.0	72.0-101.5	29.50	86.7
10	119.0	101.5-146.5	45.00	124.0

It will be seen from the second and last columns of Table 1 that the sizes used are smaller than the mid-values of the ranges they actually cover (except in the case of the smallest sizes 0 and 5.28). The reason for the differences of course lies in the form of the microscope graticule which does not provide for an arithmetical progression of diameters. Mean diameters, mean volume diameters and water contents are therefore biased towards lower

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values by using the graticule diameters as mean diameters. This is, however, a bias in the right direction since the average cloud droplet sample is one in which there are more smaller droplets than bigger droplets and the mean diameter of a number of droplets having diameters lying between certain limits should, on the average, be less than the mean of the limits. The assumption made that the graticule diameters could be taken as the mean diameters is therefore felt to be justified, within the accuracy of the size estimations.

3. Observations

The summary of the information available is given in Table 2. This shows the numbers of samples taken together with the lowest and highest levels of sampling, the object being to obtain samples throughout the depth of cloud on each flight. In addition a column is given listing the numbers of samples containing a minimum of 200 droplets, a value considered adequate for statistical purposes. The last column lists the number of samples in which no cloud droplets having diameters greater than 80 microns were found, this value being infrequently exceeded.

TABLE 2

Flight no. and date	Sampling levels		Sampling depth ft.	Numbers of samples		
	Lowest ft.	Highest ft.		Total taken	Containing at least 200 droplets	Containing no droplets having diameters > 80 μ
1 19/6/51	3,900	10,020	6,120	9	9	9
2 26/6/51	5,000	12,000	7,000	7	7	7
3 17/7/51	3,300	4,050	750	16	14	16
4 24/7/51	3,450	5,400	1,950	10	9	10
5 25/7/51	3,200	5,460	2,260	14	14	14
6 17/9/51	5,200	6,150	950	21	19	19
7 24/9/51	2,950	6,800	3,850	22	10	22
8 26/9/51	2,050	4,560	2,510	17	13	17
9 26/9/51	3,460	8,450	4,990	12	7	6
10 26/9/51	3,980	8,850	4,950	22	20	16
			Total	150	122	136

All the detailed data are listed in Table 4 which gives for each flight

(a) Height and temperature at which the sample was taken.

(b) The percentage number of droplets in each of the categories 1 to 10 in Table 1. To avoid the effect of varying airspeed these have been expressed in each case as a percentage of the total number of droplets on the sample rather than actual numbers counted.

(c) Derived data including mean diameter, mean volume diameter, number of droplets per cm.^{3} of air and cloud water content. In the calculation of these values the collection efficiency of the impactor was assumed to be unity.

(d) The constants "a" and "n" in a formula given by A.C. Best[4] for typical droplet distributions. Their derivation is discussed more fully below.

(e) Observations noted at the time the sample was taken. These include estimations of the position of sampling in the cloud, visibility and the intensity of precipitation. The absence of a report of precipitation means that no precipitation occurred but the absence of any other remark is due to the observation not having been made.

4. Results

The results are treated in three main sections

/(1)

(1) A general statistical analysis and discussion of the droplet number and water content distributions obtained as averages during each flight.

(2) The variation with height of the droplet diameters, numbers of droplets and water contents in each cloud.

(3) The applicability of a formula given by A.C. Best to the size distributions obtained.

4.1 Variation between samples

4.1.1. It is immediately obvious from Table 4 that there is little consistency between different samples. For example in flight 7, most samples contain droplets in category 6 (29.95 microns), only 7 contain droplets in category 7 (42.10 microns) and only one contains droplets in category 8 (59.9 microns). On the other hand one sample taken on this flight, no. 78, contains no droplets having diameters bigger than 10.41 microns. Furthermore, there is no consistency between the corresponding figures for samples taken at or within 100 ft. or so of the same height. Considered as a whole, the droplet distributions show how greatly the droplet content of a cumuliform cloud differs from point to point in both the horizontal and vertical.

4.1.2. Table 3 shows the droplet sizes below which are contained 10% and 90% of the total number of droplets. The flights are arranged in order of sampling thickness.

TABLE 3

Droplet sizes below which are contained 10% and 90% of total number of droplets

Flight	3	6	4	5	8	7	10	9	1	2
Sampling thickness ft.	750	950	1,950	2,260	2,510	3,850	4,950	4,990	6,120	7,000
					Microns					
10%	4.0	4.7	4.0	3.4	4.0	4.8	5.3	3.9	6.0	5.7
90%	11.0	17.0	9.3	16.3	18.3	15.0	21.0	28.0	17.6	14.5

These figures show the range of sizes in which are contained 80% of the total number of droplets. It will be seen that 10% of the droplets are of sizes less than 3-6 microns, but 10% are also comprised of droplets greater than between about 9 and 28 microns. It must be borne in mind however that the sampling efficiency of the impactor has been considered to be unity whereas in fact, its efficiency of catch for droplets smaller than about 3 microns is very low.

4.1.3. To examine the mean droplet spectra of these clouds it was first necessary to make the ranges appropriate to each size equal. This was done by dividing the mean percentages in each category, given in Table 4, by the appropriate range of diameters. The figures obtained are given below in Table 5, the flights being arranged in order of sampling depth, and are also plotted in fig. 2(a). The areas under the curves of fig. 2(a) are therefore equal, and correspond numerically to 100 droplets.

/TABLE 5

TABLE 5

Mean percentage numbers of droplets per unit range

Flight no.	No. of samples	Sampling depth ft.	Category 1 (size) 5.28	2 7.48	3 10.41	4 14.95	5 21.39	6 29.9	7 42.1	8 59.9	9 84.0	10 119.0
3	16	750	5.52	12.43	7.80	3.28	0.04	.001	.0006	.0005		
6	21	950	3.22	7.49	5.96	5.50	1.51	0.34	.066	.0015	.0017	
4	10	1,950	7.45	13.86	8.55	0.81	0.01					
5	14	2,260	5.71	7.77	5.63	4.45	1.42	0.20	.0257	.0025		
8	17	2,510	5.67	14.58	5.05	3.19	0.56	0.06	.006			
7	22	3,850	5.32	7.70	4.47	3.55	2.34	0.04	.0025	.0005		
10	22	4,950	2.54	6.09	4.29	5.70	2.51	0.54	0.110	.047	0.0085	.0002
9	12	4,990	4.63	6.50	3.43	3.77	2.04	0.84	0.200	0.200	.037	.0022
1	9	6,120	1.30	9.09	7.07	4.48	2.34	0.29	0.010			
2	7	7,000	1.64	8.34	9.10	5.35	1.18	0.23				

It appears that there is a wide variation of mean distributions between the different clouds sampled. Considering the shapes of the mean spectra in fig.2(a), it is seen that they generally have a single maximum and a variable amount of positive skew, while some have, or tend to have, a secondary maximum at a diameter greater than that of the primary one.

The peaks of these curves are given below in Table 6 in which the flights are arranged in order of increasing thickness of clouds sampled.

TABLE 6

Most common droplet sizes for each of the ten flights

Flight	3	6	4	5	8	7	10	9	1	2
Sampling depth (ft.)	750	950	1,950	2,260	2,510	3,850	4,950	4,990	6,120	7,000
Size (microns)										
Primary maxima	8	$8\frac{1}{2}$	8	$7\frac{1}{2}$	$7\frac{1}{2}$	$7\frac{1}{2}$	8	$7\frac{1}{2}$	$7\frac{1}{2}$	9
Secondary maxima							15	15		

It will be seen from Table 6 that each of the curves of fig.2(a) has its primary mode at about 8 microns, irrespective of cloud depth. In two cases secondary maxima occur at about 15 microns. It should be noted that although the secondary maxima tend to be more evident in the clouds of greatest depth this is not always so and presumably other factors as well as depth contribute to the nature of these spectra.

On the whole there is a tendency for the curves for the thinner clouds to be narrower and to have higher peaks than those for the thicker clouds and it seems that the smallest droplet sizes are more frequent in the thinner clouds. This can be better illustrated by combining the flights into two groups.

(a) Flights 3, 6, 4, 5 and 8 which have sampling depths between about 750 and 2,500 ft. and

(b) Flights 7, 10, 9, 1 and 2 which have sampling depths between 3,850 and 7,000 ft.

The average distribution in these two groups is given in Table 7 and is plotted in fig.3(a).

/TABLE 7

TABLE 7

Weighted mean of figures shown in Table 4 for two ranges of cloud thickness

Clouds with sampling depths between	Category 1	2	3	4	5	6	7	8	9	10
(a) 750 and 2,500 ft.	5.21	10.91	6.41	3.75	0.79	0.14	0.024	0.0045	0.0003	
(b) 3,850 and 7,000 ft.	3.49	7.24	5.02	4.53	2.29	0.48	0.069	0.047	0.0084	0.0004

In the above table the figures for categories 7 to 10 have been taken to 3 and 4 decimal places simply to facilitate comparison of the corresponding figures in the two groups. From fig.3(a) it will be seen that the mode diameter is about the same for the two groups of clouds, being about 8 microns. It is of interest to note that significant numbers of droplets of at least 60 microns diameter can exist on occasion in even the thinnest clouds, about 0.1% of the droplets having diameters greater than 60 microns in clouds of 750 to 2,500 ft. thickness. When the cloud depth increases to between about 4,000 and 7,000 ft. the proportion of these large droplets also increases, about 1% having diameters greater than 60 microns.

4.1.4. The next step in the analysis was to calculate the percentage volume of water in the different size ranges. To avoid presenting another large table of the size of Table 4, a typical result, for one flight only (Flight 7, which contains a large number of samples) is given in Table 8. This shows the percentage of water in the different range categories. There is a tendency for samples taken in the lower part of the cloud to have higher percentages of water content composed of small droplets and lower percentages composed of large droplets than in the upper part of the cloud.

TABLE 8 (From the results of Flight 7)

Percentages of water contents in the different size ranges

Sample no.	Height ft.	Category 1	2	3	4	5	6	7	8	9
78	2,950	28.0	56.5	15.5						
79	3,100	1.7	7.0	15.7	42.3	24.9	8.4			
80	3,400	0.3	5.7	17.1	40.0	27.5	9.4			
81	3,400	12.8	25.0	16.7	34.4	11.1				
82	3,900	0.5	3.9	13.9	25.1	28.0	10.9	0.0	17.7	
83	4,000	1.2	5.1	14.7	30.0	38.2	10.8			
84	4,500	1.3	3.2	15.0	35.6	35.9	9.0			
85	4,500	0.04	0.3	1.5	9.1	45.2	43.8			
86	4,600	0.5	1.7	7.3	23.3	54.7	12.5			
87	4,600	3.1	4.6	3.9	12.5	50.6	25.3			
88	5,000	0.9	1.4	3.7	20.2	59.0	14.8			
89	5,100	0.01	0.4	1.2	10.9	47.0	30.9	9.6		
90	5,200	0.9	1.8	3.2	8.6	50.1	24.2	11.2		
91	5,550	1.8	2.7	4.6	23.3	45.9	21.7			
92	5,650	0.3	0.4	1.7	16.4	44.3	22.7	14.2		
93	5,950	0.9	2.7	9.0	14.1	36.1	29.1	8.1		
94	6,050	0.1	1.1	2.0	13.8	44.4	38.6			
95	6,200	0.3	0.9	1.4	11.2	62.7	23.5			
96	6,200	2.3	3.1	6.3	20.6	44.7	23.0			
97	6,700	0.0	0.3	1.3	3.5	27.0	48.6	19.3		
98	6,700	0.1	0.6	0.9	11.0	48.0	29.2	10.2		
99	6,800	0.4	2.8	6.0	14.7	25.6	31.7	18.8		
Means		2.61	5.96	7.39	19.12	38.68	21.28	4.15	0.80	

4.1.5. In the same way as for the size-number analysis, cumulative mean water content curves were plotted. These are not reproduced but the droplet diameters below which are contained 10% and 90% of the total water are listed below in Table 9, the flights again being arranged in order of increasing sampling thickness.

TABLE 9

Droplet sizes below which are contained 10% and 90% of the total water content

Flight	3	6	4	5	8	7	10	9	1	2
Sampling thickness ft.	750	950	1,950	2,260	2,510	3,850	4,950	4,990	6,120	7,000
	Microns									
10%	5.5	9.0	4.0	8.0	5.5	8.0	11.5	15.5	8.0	8.0
90%	14.0	47.0	11.0	17.5	19.0	25.5	48.0	73.0	24.0	18.0

These figures, which are given to the nearest 0.5 micron, show the range of sizes in which is contained 80% of the total water content. It will be seen that 10% of the water is composed of droplets having diameters less than a value lying between 4 and 16 microns and 10% is composed of droplets having diameters greater than a value between 11 and 73 microns. In the case of water content the effect of assuming that the efficiency of catch of the impactor is unity does not give rise to appreciable inaccuracy in the figures quoted in the 10% row of Table 9, because the quantity of water contained in droplets which the impactor will not collect is a very small percentage of the total water content.

4.1.6. In order to examine the mean spectra of water content in the different size ranges for the various flights, Table 10 and fig.2(b) have been prepared. In a similar manner to Table 5, Table 10 is in terms of mean percentage water content per unit diameter range to allow comparison of water contents at different diameters.

TABLE 10

Mean percentages of water content per unit diameter range for each of the ten flights

Flight no.	Sampling depth (ft.)	Category 1	2	3	4	5	6	7	8	9	10
3	750	1.69	8.33	7.55	6.51	0.55	0.03	0.12	0.09		
6	950	0.36	2.14	2.43	4.95	3.09	1.43	0.57	0.29	0.13	
4	1,950	4.62	10.83	10.57	2.65	0.13					
5	2,260	0.50	1.91	3.39	5.68	3.78	1.30	0.37	0.08		
8	2,510	2.49	12.05	4.94	4.40	1.29	2.06	0.19			
7	3,850	0.70	2.32	1.98	3.48	5.16	1.51	0.26	0.004		
10	4,950	0.12	0.70	1.28	4.94	3.64	2.10	0.74	0.38	0.15	0.03
9	4,990	0.05	0.20	0.32	1.29	2.13	1.18	0.67	1.10	0.51	0.19
1	6,120	0.10	2.65	4.76	4.69	4.55	0.20	0.17			
2	7,000	0.11	2.13	6.90	7.04	3.67					

Compared with fig.2(a), fig.2(b) exaggerates the effect of the large droplets compared to the small since the ordinate is proportional to the cube of the diameter. Plotted in this way the droplet diameter corresponding to maximum water content does not always have a well defined mode. Diameters corresponding to peak water contents are listed in Table 11.

/TABLE 11

TABLE 11

Flight no.	3	6	4	5	8	7	10	9	1	2
Sampling thickness ft.	750	950	1,950	2,260	2,510	3,850	4,950	4,990	6,120	7,000
Diameter for peak water content (microns)	8	15	7½	15	7½	21	15	23	10	13

These values are in general considerably larger than the mode diameters for the number distributions. A comparison of the flights made in clouds with depths of 750 - 2,500 ft. and 3,850 - 7,000 ft. has been made for water content distribution with diameter in the same way as for the droplet number distributions above.

The average distribution in these two groups is given in Table 12 and is plotted in fig.3(b).

TABLE 12

Weighted mean of figures shown in Table 10 for two ranges of cloud thickness

Clouds with sampling depths between	Category 1	2	3	4	5	6	7	8	9	10
(a) 750 and 2,500 ft.	1.67	6.64	5.27	4.99	1.92	0.71	0.29	0.11	0.03	
(b) 3,850 and 7,000 ft.	0.91	1.49	2.32	3.92	3.97	1.61	0.41	0.31	0.13	0.03

The results in fig.3(b) show that as the sampling depth is increased, the water content spectrum as a whole moves towards the larger droplet diameters, maxima occurring respectively at about 8 microns and 18 microns. The water contained in droplets of diameter greater than 60 microns is similarly about 3.2% and 11.4% (corresponding to 0.1% and 1.0% in the number distributions.)

4.2. Variation of parameters

Another method of investigating the variations of droplet size and number in clouds is by computing the following parameters:-

(a) Mean droplet diameter (microns)

(b) Mean volume diameter (microns)

(c) No. of droplets per $cm.^3$

(d) Water content ($gm.m^{-3}$)

and considering the variations in these for each cloud.

(The mean volume diameter of a sample is defined to be the diameter of a droplet which contains the mean of the total volume of water in the sample.) The water content was computed from a knowledge of the area of the sample, the airspeed and the time of exposure.

These parameters were computed for all the samples and the values are given in Table 4. The first part of the subsequent analysis is devoted

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to a consideration of the variation of these parameters with height. The variations of mean diameter and mean volume diameter are clearly in the same direction and differ only in magnitude. A detailed analysis of the two parameters separately is therefore unnecessary and in what follows only the variations with height of the mean volume diameters are considered. Apart from numerical values the conclusions from this analysis may be considered to apply to both parameters.

4.2.1. Variation of mean volume diameters with height

Fig.4 shows graphs of mean volume diameter against height of sample for the ten flights. It is pointed out that it would only be possible to obtain a true indication of the vertical variation of any one of the above parameters if there were no variation in the horizontal or with time. It is largely a matter of chance whether a particular sample be taken in a thin or dense region of the cloud so that to obtain a representative indication of the variation with height it would be necessary to take a large number of samples at each level. This would enable mean values to be calculated for each level but the procedure is still not entirely satisfactory unless several aircraft make simultaneous measurements at different heights. Also, one must be certain that one has taken all the samples in the same cloud. It is often possible with isolated large cumulus clouds to confine sampling to one cloud but not, as a rule, with small clouds. Furthermore, if the tops of the cumulus clouds vary, samples taken at the same level are possibly associated with cells in different stages of development. The sampling in any one cloud took about 30 min. so that the curves cannot be regarded as representative of a particular stage of development.

4.2.1.1. The data here available do not meet the above requirements, and in particular fewer samples were taken in the two largest clouds than in the smaller ones. In fact, on those flights (1 and 2) for which the cloud depths were about 6,000 and 7,000 ft. respectively, only 9 and 7 samples were taken. These however are plotted in figs. 4(a) and 4(b) and from the curves (which were drawn by eye) there appears to be a definite tendency for the mean volume diameter to increase with height. Values near the base of the cloud are about 10 microns and they increase to about 17-20 microns near the top of the cloud.

4.2.1.2. Figs.4(g), (j) and (k) show the results for cumulus clouds between about 4,000 and 5,000 ft. thick. The 22 values plotted in fig.4(g) again display a definite tendency for mean volume diameters to increase with height. The 11 values plotted in fig.4(j) show no such tendency however, though the tendency is again perceptible in fig.4(k). The overall variation of mean volume diameter with height in these clouds is from 7 - 13 microns at the base to 23 - 27 microns at the top so that on the whole it seems from these data that droplet size does increase with height. However, it can be seen that although the average values in these clouds did not exceed about 30 microns, some much larger values of mean volume diameter were found on Flights 9 and 10 and precipitation was reported in the cloud on both of these flights. Fig.7 shows a photograph of the sample in Flight 10 in which the mean volume diameter was 40.34 microns.

4.2.1.3. Figs.4(c), (d), (e), (f) and (h) show the plots of mean volume diameters against height for small cumulus clouds of less than 2,500 ft. thickness. The evidence of an increase of mean volume diameter with height is not as pronounced as with the thicker clouds but is nevertheless there in all cases except fig. 4(f) where, probably due to the shallowness of the sampled layer, the results merely portray a large scatter. The overall variation is between about 5 and 20 microns though fig.4(d) contains none greater than about 11 microns and fig.4(f) contains two values of about 25 and 27 microns.

4.2.1.4. Figs.4(h), (j) and (k) represent plots of the values of samples

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taken in the same area and general synoptic conditions, those of 4(h) and 4(j) in the morning with a time interval of about 1½ hours and 4(k) in the afternoon another 3 hours later. These three flights therefore give some indication of the development of the droplet sizes throughout a summer day with the cloud depth increasing from about 2,500 ft. to 5,000 ft. and producing precipitation. Cloud top temperature in the case of Flight 10 was 29°F. and it seems likely that only the coalescence and not the Bergeron mechanism was operating to produce the rainfall.

4.2.1.5. In all these clouds values of mean volume diameter similar to those found near the top of the cloud can exist in the lower regions. Furthermore, due presumably to factors of change with time and space and the general inhomogeneity of the cloud, there is a large scatter from any mean curves drawn through the values.

4.2.2. Variation of water content with height

The same considerations as outlined for the analysis of mean volume diameters apply to water contents, the results of which are plotted in fig.5.

4.2.2.1. Figs.5(a) and 5(b) show the results for the two flights made in cumulus clouds 6,000 and 7,000 ft. thick. Fig.5(b) shows some slight evidence of a systematic increase with height but fig.5(a) does not. In both cases, however, the largest values are found in the upper regions of the cloud. In the main, water contents varied between 0.25 and 0.62 $gm.m^{-3}$ in fig.5(a) and between 0.17 and 0.28 $gm.m^{-3}$ in fig.5(b). However, a value of 1.07 $gm.m^{-3}$ occurred near the top of the cloud in fig.5(a) and values of 0.55 and 0.71 $gm.m^{-3}$ were found near the top of the cloud in fig.5(b). Summarising, the water contents in these two clouds of 6,000-7,000 ft. thickness largely lay between 0.2 and 0.6 $gm.m^{-3}$, but 1.1 $gm.m^{-3}$ was found on occasion. It must be remembered, however, that these results were obtained from only two flights in which only 16 samples were taken.

4.2.2.2. The results for medium sized cumulus cloud (4,500 - 5,000 ft. thick) are plotted in figs.5(g), (j) and (k). Fig.5(g) shows some tendency for water content to increase with height though the scatter is large. The overall variation is from about 0.025 to about 0.35 $gm.m^{-3}$ but the highest value of 0.55 $gm.m^{-3}$ occurs near the top of the cloud. For the 12 results plotted in fig.5(j), no really satisfactory curve can be drawn. Five of the results point to a slight increase with height while the other seven indicate local high values at all levels of the cloud. However the highest values are again found near the top of the cloud. Of the 22 samples plotted in fig.5(k), 19 lie between about 0.05 and 1.1 $gm.m^{-3}$ while the remaining three show very much larger values. Of these three, the value of 4.97 $gm.m^{-3}$, which is the highest value of water content found in M.R.F. by the method of cloud droplet sampling, again occurs near the top of the cloud which was precipitating at the time. On the whole in these four clouds the water content varied between about 0.1 and 1 $gm.m^{-3}$ with local extreme values, one of which reached almost 5 $gm.m^{-3}$. The overall variation of water content in these cumulus clouds was significantly different from one cloud to another. Where the variation throughout the greater part of the cloud was large, the local extreme values were also large.

4.2.2.3. The results for small cumulus clouds, considered as being less than 2,500 ft. thick, are plotted in figs. 5(c), (d), (e), (f) and (h). There is little, if any, indication of an increase in the values of water content with height but in view of the scatter obtained in thicker clouds this is hardly surprising. An interesting feature of fig.5(f) is that the average values of water content are fairly high although the cloud is only about 1,000 ft. thick.

It is concluded from the results for the small cumulus clouds that the variation of water content within different clouds is different from cloud to cloud and, from fig.5(f), that comparatively large values can occur in thin

/clouds.

clouds. In the main values of water content varied between about 0.01 and 0.5 gm.m^{-3} but values up to 1.4 gm.m^{-3} also occurred.

4.2.2.4. In order to see how the observed values of water content compared with the theoretical adiabatic values, the latter were computed using cloud base temperatures from the flight data (where given) or from the relevant Te-Phi-gram and the values are plotted as full line curves in fig.5. It will be seen that on the whole computed values of water content are greater than the observed values but this is not always the case. For example, some of the observed values on flights 9 and 10 were greater than the calculated values but this could be explained by the fact that it was raining in these clouds. On the other hand although no rain was reported in the cloud sampled on flight 6 (which was only 1,000 ft. thick) a large number of values of water content greater than the theoretical adiabatic values were observed in the lowest 500 feet.

Adiabatic values of water content necessarily increase uniformly from zero at the cloud base to a maximum value at the cloud top and would strictly be found only in those regions of the cloud in which no entrainment, mixing or precipitation occurs.

Mixing and entrainment will cause the actual values to be less than those calculated from adiabatic ascent in which there is no interchange of air between the rising cloud mass and the environment, and therefore lower values of water content would suggest some interchange. As most of the values observed are lower it seems likely that this interchange in fact occurs over most of the cloud, although not necessarily everywhere within it. On the other precipitation would normally result in some increase of the values lower down at the expense of the higher regions. The extent of any mixing and precipitation obviously depends on many factors such as speed of updraughts, state of development and age of the cloud so that all that can be concluded safely from these results is that the application of calculated water contents to given clouds is at the best a rough process and in the main except where there is precipitation will usually lead to over estimates.

4.2.3. Variation of the number of droplets per $cm.^3$ with height

Graphs showing the variation of numbers of droplets per $cm.^3$ with height are shown plotted in fig.6. There was nowhere any evidence of a systematic variation with height and in the main there were between 100 and 300 droplets per $cm.^3$ in any of the clouds. However, local extreme values, as high as 976 $cm.^{-3}$ and as low as 19 $cm.^{-3}$ occurred and there was a tendency for higher values to be found near the base of the cloud.

4.2.4. Variation of water content with mean volume diameter and number of droplets per $cm.^3$

The relationship between mean volume diameter "D", and water content "W" and number of droplets per $cm.^3$ "N" is evidently

$$W = \frac{\pi}{6} N D^3$$

Curves of W against D for different values of N are shown superimposed on the plotted points for the 150 samples in fig.8 giving an overall presentation. A mean curve, shown dotted, has been drawn through the points. It will be seen that the mean curve differs very little from the curve corresponding to N = 150 for mean volume diameters greater than about 20 microns and that all but 4 of the 150 samples lie between the curves for N = 25 and N = 500. The mean curve shows that the tendency is for higher values of water content to be due to higher values of mean volume diameter rather than higher values of number of droplets per $cm.^3$.

4.3. An examination of Best's equation for the droplet distribution in clouds

An equation suggested by Best[4] which is frequently used to relate

/quantities

quantities of water and droplet size within a cloud is

$$1-F = e^{-\left(\frac{d}{a}\right)^n}$$

where F is the fraction of liquid water comprised of droplets with diameters less than "d" and where "a" and "n" are constants. The equation can be rewritten in the form

$$\log_{10} \log_{10} \frac{1}{1-F} = n\log_{10} d - (n\log_{10} a + 0.3617)$$

which represents a straight line of slope n. The constant "a" is easily seen to be the value of d for which $\log_{10} \log_{10} \frac{1}{1-F} = -0.3617$ (or $\bar{1}.6383$).

To find values of the constants "a" and "n" values of $\log_{10} \log_{10} \frac{1}{1-F}$ were plotted against $\log_{10} d$ (d having the values 6.38, 8.95, 12.68 etc. as given in Table 1 for the upper limits of the ranges covered by the graticule circles) for all the samples.

For many of the samples the relationship between $\log_{10} \log_{10} \frac{1}{1-F}$ and $\log_{10} d$ was not that of a straight line but a curve. For most of the samples however, the curvature was not very great and it was possible to draw the best straight lines through the points fairly accurately by eye. (It was not considered worthwhile to undertake the task of computing the best straight lines by the method of least squares.) Fig.9 shows plots of $\log_{10} \log_{10} \frac{1}{1-F}$ against $\log_{10} d$ for the 9 samples of Flight 1.

For the largest droplet size present, F = 1 and $\log_{10} \log_{10} \frac{1}{1-F}$ = infinity. If F be taken as 0.99 the value of $\log_{10} \log_{10} \frac{1}{1-F}$ drops to 0.301. Hence, for values of F approximately equal to 1, a very small change in F makes a significant difference to the nature of the curve. For this reason it was decided that the point corresponding to the largest droplet size present was unrepresentative and was not used in assessing the best straight lines. The percentage of water considered was therefore that for values of $\log_{10} \log_{10} \frac{1}{1-F}$ up to the greatest but one size.

Within the above restrictions it was possible to obtain values of "a" and "n" for 108 of the 150 samples. For the remaining 42 samples the curvature was considered too great to merit drawing straight lines. The main reason for this appears to be because the largest droplets of some samples, while being small in number, have a large size range. Deviations from a straight line will, however, always occur to some extent.

The 108 values of "a" and "n" are listed in Table 4. Mean values are also given for all the samples in each flight and the mean values for all the 108 samples were "a" = 23.0 and "n" = 5.1.

In an attempt to correlate the values of the two constants with other parameters graphs were plotted of the constants against (1) water content, (2) number of droplets per $cm.^3$ and (3) maximum diameters. It was found that

(1) "a" increased in a fairly regular manner and "n" decreased in a most irregular manner with increasing water content,

(2) "a" and "n" did not show any regular variation with number of droplets per $cm.^3$,

(3) "a" increased almost linearly and "n" decreased rather irregularly with increasing maximum droplet diameter.

/Graph

Graphs showing the variations of "a" and "n" with maximum droplet diameter and water content are reproduced in fig.10. The most useful of the four curves (which were drawn by eye) is that shown in fig.10(a) from which it will be seen that the points lie fairly close to a straight line of slope $^{3}/_{2}$ which passes through the origin. It therefore seems that in practice a good approximation to the value of the constant "a" is about $^{2}/_{3}$ of the diameter of the largest droplet present. By way of confirmation, the 108 values of "a" have been listed, regardless of flight, under the representative diameters used, viz. 10.41, 14.95, 21.39 microns etc. The table obtained showed a scatter which was to be expected due to the representative diameters not being the true diameters as discussed in para. 2 and to different samples having different numbers of droplets at the maximum size. The complete table is not reproduced but the mean values are shown below in Table 13.

TABLE 13

Mean values of Best's constant "a" for different maximum droplet sizes

Maximum diameter (microns)	10.41	14.95	21.39	29.95	42.1	59.9	84	119
No. of samples	7	12	22	32	22	7	2	4
Mean "a" (microns)	7.3	12.05	14.45	22.0	25.42	43.4	52.5	70.7
Ratio $\frac{a}{D_{max.}}$	0.70	0.81	0.67	0.73	0.60	0.72	0.63	0.59

The weighted mean value of the ratio $\frac{a}{D_{max.}}$ by this method is 0.68 which agrees well with the value quoted above.

Compared with the variation of "a" with maximum droplet diameter, that of "n" is not as clearly defined. However it seems that a reasonable approximation to "n" can be obtained from fig.10(b).

It is possible to carry out a considerable amount of further statistical research on the variations of "a" and "n" with different parameters but there seems little to be gained by such an undertaking.

5. Discussion

Impactor techniques for cloud droplet sampling have been used by other workers (Mazur 1943[1], Diem 1948[5], Squires and Gillespie 1952[6]). The work of Squires and Gillespie in Australia was largely devoted to the presentation of a new type of cloud droplet impactor (which also used magnesium oxide coated slides) and results were given for only nine impactions taken at one level on one flight through a cumulus cloud from which precipitation fell. The highest value of water content found was 1.6 $gm.m^{-3}$ which is not in disagreement with values published in this report. However the largest value of the number of droplets per $cm.^{3}$ found was 93 and this seems rather small. The data given by Diem and Mazur have been analysed by Best[7]. Mazur gives results from 11 flights in cumulus clouds but the greatest number of samples taken on any flight was only six. The largest mean water content he found was 0.49 $gm.m^{-3}$ and the largest mean value of the mean volume diameter was 17.3 microns. Diem's results which were obtained using an oil technique include only two flights in cumulus clouds with maximum values of water content and mean volume diameter of 0.21 $gm.m^{-3}$ and 17.1 microns respectively. The results of the present paper are not in disagreement with the results of these workers but, in virtue of the much greater number of samples examined, present a fuller picture of the processes.

/The

The manner in which water is distributed in droplet form throughout a cumulus cloud depends primarily on the life and extent of the cloud. An exact analysis requires knowledge of the positions in the cloud at which the samples were taken and further requires that all samples be taken at the same time. The best that can be done to satisfy the first requirement is to state roughly the location within the cloud at which the sample was taken though this is not always obvious. The second requirement cannot be fulfilled at all and in consequence results which have been obtained using a single shot impactor must be treated with reserve especially when several samples are grouped together to obtain mean values which are considered to be representative of the cloud. It should also be remembered that impactors of the type used for this work and in quoted references tend to underestimate the numbers of very small droplets. This will affect droplet number distributions more than water content distributions.

However with these reservations in mind the following conclusions may be drawn from this report.

1. Mean spectra of droplet diameter against droplet number have a mode at about 8 microns. A secondary maximum at about 15 microns was partly in evidence in some clouds and fully evident in others.

The primary mode at 8 microns could suggest that condensation nuclei produce droplets which soon grow to this size though the reason why this should represent a preferred state is not clear. It is thought that the establishment of the secondary mode is associated with development within the cloud and occurs at the expense of the 8-micron diameter droplets by coalescence. In clouds of greater thickness than those examined it is possible that the secondary mode will be displaced towards larger droplet diameters.

2. If mean droplet diameter is plotted against water content it is found that for clouds between about 750 and 2,500 ft. thick the mode is at about 8 microns but for clouds between about 4,000 and 7,000 ft. thick the mode is at about 18 microns.

This increase of the mode diameter represents another aspect of development from a small cloud to a bigger one. Larger clouds have higher water contents and the bulk of the water is contained in larger droplets.

3. In clouds between 1,000 and 2,500 ft. thick about one droplet in 1,000 has a diameter larger than 60 microns and these large droplets account for about 3.2% of the liquid water. In clouds between about 4,000 and 7,000 ft. thick about one droplet in 100 has a diameter larger than 60 microns and accounts for about 11.4% of the liquid water.

4. Mean droplet diameters and mean volume diameters tend to increase with height, the latter having values of about 5-10 microns near cloud bases and 20-25 microns near cloud tops. Higher values occur locally within the cloud and values of about 45 microns have been noted in clouds between 4,000 and 5,000 ft. thick which were precipitating.

5. Water content tends to increase with height and to have larger values in thicker clouds. In the main, values are up to about 0.5 $gm.m^{-3}$ in clouds up to about 2,500 ft. thick and up to about 1.0 $gm.m^{-3}$ in clouds of up to about 7,000 ft. thick. Higher values occur locally however and a value of almost 5 $gm.m^{-3}$ has been observed in cloud between 4,000 and 5,000 ft. thick which was precipitating.

On the whole observed values of water content are less than adiabatic values and this is doubtless due to dilution. However, higher-than-adiabatic values occur and while in some cases this may be due to modification caused by precipitation within a cloud this is not always so. In general it seems that adiabatic values are an unreliable guide to the disposition of water within a cloud.

/6.

6. The number of droplets per cm.^{3} is in the main between 100 and 300 in most parts of cumulus clouds but there is a trend towards higher values near cloud bases.

7. Higher water contents in cumulus cloud appear to be due to larger droplets rather than to greater number of droplets per cm.^{3}.

8. The formula relating quantities of water and droplet diameter given by Best over-estimates the importance of the larger droplets in relation to the smaller droplets to such an extent that it was possible to obtain values of the parameters "a" and "n" for only about 70% of the samples. However it appears that the value of "a" is governed by the largest size of droplet on the sample and a good approximation to it may be taken as 2/3 of the diameter of the largest droplet. Similarly a reasonable estimation of the value of "n" can be obtained from its variation with maximum droplet diameter (fig.10(b)) though the nature of the variation is not as well defined as in the case of "a".

An examination of Best's formula has been made in a somewhat different manner by Boucher and Bartnoff (8). They found, considering the results of Diem, that on the whole both Best's formula and another derived by Atlas and Bartnoff(8) were valid. For large droplet diameters the contribution of the theoretical distribution function F given by Best was greater than for the observed distributions. This is in agreement with what has been stated above.

9. Future work in the field of cloud droplet distribution can more usefully be undertaken using a technique which allows continuous sampling during a traverse through a cloud. Neglecting the time taken for the aircraft to traverse the cloud, this will enable reasonably accurate investigations of the droplet distribution at a given level to be made and successive traverses at the same level would provide valuable information on cloud development. In particular such an instrument would be capable of checking the theory of Ludlam (9) which requires small numbers of large droplets (of order 40-60 microns diameter) in the base of a cloud to initiate precipitation. It is strongly recommended that time and effort be expended in the pursuit of such an instrument, possibly along the lines of an instrument described by Hacker (10). The possibility is being studied in M.R.F. but instrumentation and analysis involved in this project would be formidable.

6. Acknowledgments

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TABLE 4

Details of height, number, size, water content, temperature and remarks for individual samples. Flight 1. 19/6/51

Item no.											Mean values
1.	Sample No.	1.	2.	3.	4.	5.	6.	7.	8.	9.	-
2.	Sampling height, ft.	3,900	4,300	5,000	6,000	7,000	8,000	8,900	9,000	10,020	-
3.	Temperature	-	-	-	-	-	-	-	-	-	-
4.	Total no. of drops	2,034	833	335	899	449	538	400	489	528	-
5.	Percentage no. of droplets in:-										
	Category 1. (5.28 microns)	-	1.80	-	1.66	2.00	16.17	0.75	1.02	20.26	4.85
6.	Category 2. (7.48 microns)	35.00	21.36	8.95	43.15	24.72	22.11	5.50	18.40	31.06	23.36
7.	Category 3. (10.41 microns)	55.06	54.26	20.89	28.58	33.40	16.35	8.25	17.38	3.40	26.39
8.	Category 4. (14.95 microns)	9.68	20.64	24.47	22.24	35.41	28.25	40.75	38.24	1.89	24.61
9.	Category 5. (21.39 microns)	0.24	1.92	42.38	3.67	4.00	16.17	42.75	23.72	23.48	17.59
10.	Category 6. (29.95 microns)	-	-	2.98	0.44	0.44	0.55	2.00	1.22	19.31	2.99
11.	Category 7. (42.10 microns)	-	-	0.29	0.22	-	0.37	-	-	0.56	0.16
12.	Category 8. (59.9 microns)	-	-	-	-	-	-	-	-	-	-
13.	Category 9. (84.0 microns)	-	-	-	-	-	-	-	-	-	-
14.	Category 10. (119.0 microns)	-	-	-	-	-	-	-	-	-	-
15.	No. of droplets cm.$^{-3}$	976	397	160	427	214	248	191	233	252	344
16.	Mean diameter (microns)	9.90	10.88	16.6	10.64	11.76	12.23	17.20	14.45	15.10	13.19
17.	Mean volume diameter (microns)	9.90	11.62	18.4	12.35	12.93	14.80	18.35	16.04	20.10	14.94
18.	Water content (gm. m.$^{-3}$)	0.50	0.33	0.52	0.43	0.25	0.44	0.62	0.51	1.07	0.52
19.	Best's constant "a"	13.8	-	22.9	-	17.4	21.9	-	21.9	-	19.6
20.	Best's constant "n"	3.7	-	5.6	-	5.7	4.9	-	5.3	-	5.0
	Remarks										
21.	Approximate position of sample	-	-	-	-	-	-	-	-	-	-
22.	Precipitation reported	-	-	-	-	-	-	-	-	-	-
23.	Estimated visibility (yd.)	-	-	-	-	-	-	-	-	-	-
24.	Additional remarks	-	-	-	-	-	-	-	-	-	-

Table 4 (contd.)
Flight 2. 26/6/51

Item no.	10.	11.	12.	13.	14.	15.	16.	Mean values
1.	5,000	7,000	8,000	9,000	10,000	11,000	12,000	-
2.	-	-	-	-	-	-	-	-
3.	507	742	446	597	636	628	537	-
4.	6.31	-	4.48	27.13	1.25	1.43	2.23	6.12
5.	39.64	18.59	23.09	31.65	21.22	7.80	8.00	21.43
6.	33.53	80.86	37.21	15.41	40.56	12.73	17.31	33.94
7.	20.11	0.53	24.21	17.08	36.79	55.57	51.21	29.36
8.	0.39	-	10.76	8.37	0.15	21.65	20.85	8.88
9.	-	-	0.22	0.33	-	0.79	0.37	0.24
10.	-	-	-	-	-	-	-	-
11.	-	-	-	-	-	-	-	-
12.	-	-	-	-	-	-	-	-
13.	-	-	-	-	-	-	-	-
14.	242	354	212	284	293	299	255	277
15.	9.75	9.97	11.88	9.93	11.43	14.30	14.86	11.73
16.	10.75	10.00	13.48	12.72	11.82	16.50	16.07	13.05
17.	0.17	0.19	0.27	0.27	0.28	0.71	0.55	0.35
18.	14.1	10.7	19.1	19.9	14.8	21.4	20.4	17.1
19.	6.9	14.3	4.0	3.6	8.0	5.9	6.1	7.0
20.	-	-	-	-	-	-	Top	
21.	-	-	-	-	-	-	-	
22.	-	-	-	< 20	< 20	< 10	< 10	
23.	-	-	Hail at higher level	-	-	Icing	Icing	
24.								

Flight 3. 17/7/51

Item no.	17.	18.	19.	20.	21.	22.	23.	24.
1.	3,300	3,400	3,400	3,450	3,700	3,750	3,900	3,950
2.	-	-	-	-	-	-	-	-
3.	439	580	452	309	548	497	407	141
4.	12.30	39.65	3.09	79.61	46.71	8.24	23.83	32.62
5.	34.16	44.31	31.41	20.06	41.24	24.54	34.88	18.43
6.	41.00	15.17	49.11	-	10.03	62.77	27.02	29.78
7.	12.30	0.68	16.15	0.32	1.82	4.42	13.51	17.73
8.	-	0.17	-	-	0.18	-	0.73	1.41
9.	0.22	-	-	-	-	-	-	-
10.	-	-	-	-	-	-	-	-
11.	-	-	-	-	-	-	-	-
12.	-	-	0.22	-	-	-	-	-
13.	-	-	-	-	-	-	-	-
14.	-	-	-	-	-	-	-	-
15.	211	277	214	139	255	248	179	70
16.	9.44	7.10	10.10	5.75	6.92	9.57	8.92	9.20
17.	10.27	7.64	11.97	5.78	7.48	9.88	10.00	10.58
18.	0.12	0.07	0.19	0.01	0.06	0.13	0.09	0.04
19.	-	-	-	6.8	-	12.3	13.2	15.1
20.	-	-	-	3.7	-	6.7	5.4	5.0
21.	-	-	-	-	-	-	-	-
22.	-	-	-	-	-	-	-	-
23.	-	-	-	-	-	-	-	-
24.	-	-	-	-	-	-	-	-

Table 4
Flight 3(contd.)

Item no.	25.	26.	27.	28.	29.	30.	31.	32.	Mean values
1.	3,950	4,000	4,000	4,000	4,050	4,050	4,050	4,050	-
2.	-	-	-	-	-	-	-	-	-
3.	291	434	142	422	527	598	236	476	-
4.	5.84	40.32	7.04	12.79	4.11	0.66	8.89	4.62	20.66
5.	29.89	50.23	14.78	83.17	15.86	22.57	18.22	27.31	31.94
6.	59.45	9.21	20.42	4.02	37.72	44.81	16.94	37.81	29.08
7.	4.81	-	57.74	-	42.30	31.93	55.08	29.41	18.01
8.	-	-	-	-	-	-	0.84	0.84	0.26
9.	-	-	-	-	-	-	-	-	0.01
10.	-	0.22	-	-	-	-	-	-	0.01
11.	-	-	-	-	-	-	-	-	0.01
12.	-	-	-	-	-	-	-	-	-
13.	-	-	-	-	-	-	-	-	-
14.	139	216	66	208	389	298	113	222	184
15.	9.49	6.97	12.30	7.37	13.68	11.20	12.06	10.80	9.10
16.	9.84	8.10	12.15	7.45	14.36	13.33	13.00	11.70	10.05
17.	0.07	0.06	0.08	0.05	0.38	0.26	0.13	0.19	0.12
18.	12.0	-	17.8	8.5	17.4	14.1	14.8	-	13.2
19.	8.3	-	5.4	12.5	10.5	7.4	6.0	-	7.1
20.	-	-	-	-	-	-	-	-	-
21.	-	-	-	-	-	-	-	-	-
22.	-	-	-	-	-	-	-	-	-
23.	-	-	-	-	-	-	-	-	-
24.	-	-	-	-	-	-	-	-	-

Flight 4. 24/7/51

Item no.	33.	34.	35.	36.	37.	38.
1.	3,450	3,650	4,000	4,500	4,500	4,500
2.	-	-	-	-	-	-
3.	546	227	339	673	372	221
4.	96.33	14.53	21.23	9.80	55.64	66.51
5.	3.66	62.55	45.72	32.98	43.01	33.03
6.	-	21.58	32.15	50.66	1.34	0.45
7.	-	1.32	0.58	6.53	-	-
8.	-	-	0.29	-	-	-
9.	-	-	-	-	-	-
10.	-	-	-	-	-	-
11.	-	-	-	-	-	-
12.	-	-	-	-	-	-
13.	-	-	-	-	-	-
14.	272	110	173	324	180	107
15.	5.37	7.90	8.04	9.25	6.28	6.04
16.	5.39	8.30	8.57	9.81	6.52	6.23
17.	0.02	0.03	0.06	0.16	0.03	0.01
18.	-	11.0	12.6	12.3	7.4	7.1
19.	-	6.3	4.1	6.5	6.1	6.3
20.	base	-	- just above base	-	-	
21.	-	-	-	-	-	-
22.	-	-	-	-	-	-
23.	wispy	-	-	-	-	-
24.						

Table 4
Flight 4 (contd.)

Item no.	39.	40.	41.	42.	Mean values
1.	5,000	5,000	5,000	5,400	-
2.	-	-	-	-	-
3.	306	644	715	62	-
4.	3.26	4.50	7.41	-	27.92
5.	10.13	25.77	46.01	53.22	35.61
6.	78.75	64.59	40.41	29.03	31.90
7.	7.51	4.96	6.01	17.74	4.46
8.	0.32	0.15	0.13	-	0.09
9.	-	-	-	-	-
10.	-	-	-	-	-
11.	-	-	-	-	-
12.	-	-	-	-	-
13.	-	-	-	-	-
14.	143	311	338	31	199
15.	10.32	9.68	8.99	9.54	8.14
16.	10.69	10.09	9.57	10.45	8.56
17.	0.09	0.16	0.15	0.02	0.07
18.	13.5	13.2	12.9	14.8	11.6
19.	8.0	6.9	6.3	3.1	5.9
20.	-	edge	-	tops	-
21.	-	-	-	-	-
22.	-	-	100	-	-
23.	-	wispy	quite dense	-	-
24.					

Flight 5. 25/7/51

Item no.	43.	44.	45.	46.	47.	48.	49.	50.	51.	52.	53.	54.
1.	3,200	3,200	3,500	3,500	3,800	3,800	4,200	4,200	4,500	4,800	4,800	5,100
2.	-	-	-	-	-	-	-	-	-	-	-	-
3.	639	823	417	455	996	352	497	919	237	226	469	328
4.	19.40	37.30	6.23	52.96	49.59	3.12	35.41	11.20	3.79	17.25	29.63	12.80
5.	30.98	28.91	16.06	21.31	31.22	14.48	20.32	15.56	18.98	18.58	15.99	28.35
6.	30.04	19.68	22.06	6.81	10.34	23.01	10.46	25.68	16.87	42.03	14.49	38.41
7.	17.05	12.63	35.97	4.83	7.02	46.02	19.31	32.10	35.02	22.12	19.61	17.68
8.	2.50	1.21	17.50	5.05	1.40	11.93	11.46	13.16	23.62	-	14.92	2.74
9.	-	0.24	2.15	4.61	0.40	1.42	2.61	2.06	1.68	-	4.47	-
10.	-	-	-	3.73	-	-	0.40	0.21	-	-	0.85	-
11.	-	-	-	0.65	-	-	-	-	-	-	-	-
12.	-	-	-	-	-	-	-	-	-	-	-	-
13.	-	-	-	-	-	-	-	-	-	-	-	-
14.	296	364	193	214	448	156	247	406	101	113	233	149
15.	9.58	8.40	13.60	10.22	8.98	13.50	10.76	12.75	18.78	10.00	12.10	10.03
16.	10.94	10.02	15.62	18.36	9.28	15.05	14.46	15.12	16.14	10.94	16.18	10.60
17.	0.20	0.19	0.38	0.70	0.19	0.28	0.41	0.78	0.22	0.08	0.52	0.09
18.	15.5	17.0	22.4	36.3	17.8	19.9	19.5	24.0	22.9	14.8	30.2	14.1
19.	4.8	3.2	4.9	2.6	2.0	6.3	4.2	3.9	4.9	5.0	2.6	5.4
20.	-	-	-	-	-	-	-	-	-	-	-	-
21.	-	-	-	-	-	-	-	-	-	-	-	-
22.	-	-	-	-	-	-	-	-	-	-	-	-
23.	-	-	-	-	-	-	-	-	-	-	-	-
24.	-	-	-	-	-	-	-	-	-	-	-	-

Table 4
Flight 5 (contd.)

Item no.	55.	56.	Mean values
1.	5,350	5,400	-
2.	-	-	-
3.	415	1,068	-
4.	16.38	4.11	21.37
5.	9.15	9.73	19.97
6.	17.34	16.57	20.98
7.	35.90	37.17	24.46
8.	15.90	27.99	10.67
9.	4.81	4.40	2.06
10.	0.48	-	0.41
11.	-	-	0.05
12.	-	-	-
13.	-	-	-
14.	193	514	259
15.	13.40	15.50	11.97
16.	14.84	17.54	13.93
17.	0.33	1.45	0.42
18.	29.5	25.1	22.1
19.	3.2	6.3	4.2
20.	tops	tops	-
21.	-	-	-
22.	-	-	-
23.	-	-	-
24.			

Flight 6. 17/9/51

Item no.	57.	58.	59.	60.	61.	62.	63.	64.	65.	66.	67.	68.
1.	5,200	5,200	5,300	5,400	5,400	5,450	5,500	5,500	5,500	5,750	5,750	5,750
2.	33.2	33.3	33.7	33.0	33.0	33.1	32.9	33.1	32.7	32.8	32.2	31.8
3.	366	344	416	316	476	304	292	458	327	305	326	662
4.	16.66	24.70	3.12	3.48	5.25	14.47	1.36	15.28	7.33	26.88	10.12	42.29
5.	15.84	18.60	6.49	8.54	12.60	20.72	5.13	14.41	11.92	36.72	17.17	48.48
6.	22.95	23.54	11.53	21.51	18.69	14.47	14.38	18.99	22.62	25.90	18.09	6.79
7.	32.24	24.70	44.47	46.20	49.36	18.42	36.30	29.03	43.73	8.85	19.63	1.96
8.	9.28	7.26	33.41	18.35	12.60	8.55	21.91	10.91	9.48	0.65	28.22	0.30
9.	2.18	1.16	0.96	1.89	1.26	13.48	11.98	8.07	3.97	0.32	5.52	-
10.	0.27	-	-	-	0.21	6.25	7.19	3.05	0.91	0.32	0.61	0.15
11.	0.54	-	-	-	-	2.96	1.71	0.21	-	-	0.61	-
12.	-	-	-	-	-	0.65	-	-	-	0.32	-	-
13.	-	-	-	-	-	-	-	-	-	-	-	-
14.	168	188	188	152	218	139	150	218	152	227	141	306
15.	12.35	10.72	15.92	14.48	13.70	17.40	19.68	14.33	13.78	8.85	15.00	6.98
16.	16.26	13.06	17.30	16.06	15.40	27.20	25.06	19.34	16.46	14.62	19.06	8.18
17.	0.38	0.22	0.51	0.33	0.42	1.47	1.25	0.81	0.35	0.37	0.51	0.09
18.	-	20.9	21.9	21.9	-	61.7	-	-	-	-	-	-
19.	-	3.6	6.1	5.9	-	2.7	-	-	-	-	-	-
20.	-	-	-	-	-	-	-	-	-	-	-	-
21.	-	-	-	-	-	-	-	-	-	-	-	-
22.	-	100	100	50	50	50	50	50	50	-	-	-
23.	-	-	-	-	-	-	-	-	-	-	-	-
24.												

Table 4
Flight 6 (contd.)

Item no.	69.	70.	71.	72.	73.	74.	75.	76.	77.	Mean values
1.	5,750	5,750	5,750	5,750	5,750	5,800	6,100	6,150	6,150	-
2.	32.0	32.0	31.7	31.3	31.4	31.6	30.6	32.1	31.9	-
3.	135	183	379	356	219	580	366	447	340	-
4.	4.44	1.63	35.35	3.37	9.13	2.75	7.65	11.40	6.17	12.04
5.	22.96	14.20	49.07	20.50	26.94	7.58	18.85	18.56	9.11	19.25
6.	27.40	15.84	13.98	30.61	22.37	51.20	27.86	28.85	29.41	22.24
7.	26.66	36.61	1.58	40.44	31.96	37.41	37.15	28.18	39.41	30.20
8.	15.55	20.21	-	4.77	7.30	1.03	5.73	9.84	12.64	11.33
9.	2.96	9.83	-	0.28	2.28	-	2.45	2.46	2.64	3.51
10.	-	1.63	-	-	-	-	0.27	0.67	0.29	1.04
11.	-	-	-	-	-	-	-	-	0.29	0.30
12.	-	-	-	-	-	-	-	-	-	0.05
13.	-	-	-	-	-	-	-	-	-	-
14.	62	84	173	200	91	272	168	212	153	173
15.	13.00	16.27	7.24	12.05	11.82	11.83	12.32	12.33	13.75	13.04
16.	15.48	19.40	7.76	13.26	14.04	12.54	14.52	15.18	16.50	15.79
17.	0.12	0.32	0.04	0.27	0.15	0.28	0.27	0.39	0.36	0.42
18.	-	-	-	-	-	15.9	-	-	-	28.4
19.	-	-	-	-	-	7.10	-	-	-	5.1
20.	-	-	-	-	-	-	tops	tops	tops	-
21.	-	-	-	-	-	-	-	-	-	-
22.	-	-	100	-	-	-	-	-	-	-
23.	-	-	-	-	-	-	-	-	-	-
24.	-	-	-	-	-	-	-	-	-	-

Flight 7. 24/9/51

Item no.	78.	79.	80.	81.	82.	83.
1.	2,950	3,100	3,400	3,400	3,900	4,000
2.	-	50.0	47.5	47.3	45.7	45.0
3.	469	183	131	304	442	347
4.	56.07	20.21	4.58	50.32	9.72	17.57
5.	39.87	29.86	29.77	34.53	26.01	25.93
6.	4.05	24.04	32.82	8.55	34.16	27.95
7.	-	21.85	25.95	5.92	20.81	19.30
8.	-	4.37	6.10	0.65	7.91	8.35
9.	-	0.54	0.76	-	1.13	0.86
10.	-	-	-	-	-	-
11.	-	-	-	-	0.22	-
12.	-	-	-	-	-	-
13.	-	-	-	-	-	-
14.	207	77	64	145	197	173
15.	6.52	10.10	11.32	7.18	11.28	10.72
16.	6.66	11.98	12.96	8.32	14.04	12.90
17.	0.03	0.07	0.07	0.04	0.28	0.18
18.	6.61	19.5	-	13.8	-	20.9
19.	10.0	3.8	-	2.7	-	3.6
20.	-	base	-	-	-	-
21.	slight	-	-	-	-	heavy
22.	-	-	-	-	-	100
23.	-	-	-	-	wispy	-
24.						

Table 4
Flight 7 (contd.)

Item no.	84.	85.	86.	87.	88.	89.	90.	91.	92.	93.	94.	95.	96.	97.	98.	99.	Mean values
1.	4,500	4,500	4,600	4,600	5,000	5,100	5,200	5,550	5,650	5,950	6,050	6,200	6,200	6,700	6,700	6,800	–
2.	43.5	43.5	43.0	43.0	42.0	42.1	41.0	40.0	40.0	38.0	39.0	38.5	39.0	37.5	38.0	39.5	–
3.	133	42	58	195	46	178	296	217	162	274	76	374	282	91	92	273	–
4.	19.54	2.38	12.06	46.66	23.91	0.56	28.71	34.56	14.81	20.43	6.57	11.76	38.65	–	7.60	10.98	19.89
5.	17.29	7.14	15.51	24.10	13.04	8.42	19.59	18.34	6.79	21.53	17.10	12.56	18.79	9.89	10.86	29.30	19.79
6.	30.07	11.90	24.13	7.69	13.04	8.98	12.50	11.52	9.87	27.37	11.84	7.75	13.82	15.38	6.52	23.07	16.68
7.	24.06	23.80	25.86	8.20	23.91	28.65	11.48	19.81	32.09	14.23	26.31	21.39	15.24	13.18	26.08	19.04	19.42
8.	8.27	40.47	20.68	11.28	23.91	42.13	22.97	13.36	29.62	12.40	28.94	40.90	11.34	35.16	39.13	11.35	19.06
9.	0.75	14.28	1.72	2.05	2.17	10.11	4.05	2.30	5.15	3.64	9.21	5.61	2.12	23.07	8.69	5.12	4.72
10.	–	–	–	–	–	1.12	0.67	–	1.23	0.36	–	–	–	3.29	1.08	1.09	0.40
11.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.01
12.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
13.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
14.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
15.	62	19	29	89	20	75	130	101	71	127	36	178	136	41	39	129	97
16.	11.04	18.18	13.13	9.09	12.95	18.40	12.40	11.00	15.60	11.55	15.78	15.95	10.22	20.13	17.20	10.50	12.67
17.	13.10	20.60	15.48	12.98	15.82	20.60	16.48	14.16	18.72	14.98	18.54	18.54	13.54	23.36	21.05	16.32	15.45
18.	0.07	0.09	0.05	0.11	0.05	0.37	0.31	0.15	0.26	0.23	0.12	0.59	0.17	0.27	0.17	0.29	0.18
19.	20.9	27.5	22.9	–	24.0	29.5	28.8	24.5	25.7	26.9	26.9	26.9	24.0	33.9	29.5	–	24.1
20.	3.6	5.5	4.2	–	3.7	4.4	3.4	3.2	5.0	3.3	4.9	4.4	3.17	4.5	4.4	–	4.3
21.	–	–	–	–	–	–	–	–	–	edge	edge	–	–	–	top edge	top centre	–
22.	moderate	–	slight	slight	–	–	–	–	moderate	moderate	moderate	–	–	–	–	–	–
23.	–	–	200	200	–	200	200	–	200	–	100	100	100	–	–	–	–
24.	wispy	wispy	–	–	wispy	–	–	thick	–	–	–	–	–	wispy	–	–	–

Table 4
Flight 8. 26/9/51

Item no.																		Mean values
1.	100.	101.	102.	103.	104.	105.	106.	107.	108.	109.	110.	111.	112.	113.	114.	115.	116.	
2.	2,050	2,050	2,310	2,310	2,320	2,340	2,350	2,790	2,790	2,800	2,800	3,300	3,300	3,320	3,320	4,530	4,560	-
3.	52.0	51.0	49.6	49.8	50.0	49.4	49.4	47.5	47.9	47.8	48.8	46.3	45.6	46.3	45.6	44.6	43.3	-
4.	453	332	603	483	293	1,261	190	569	638	152	582	65	493	584	90	373	364	-
5.	42.38	53.61	37.98	83.64	26.96	14.90	34.21	3.16	2.03	10.52	17.52	4.16	3.85	-	11.11	3.75	10.44	21.22
6.	53.42	44.57	58.54	16.14	42.66	79.06	65.26	35.32	13.63	55.26	69.75	16.92	19.47	4.62	25.55	8.31	28.57	37.47
7.	3.31	1.50	3.48	0.20	21.84	5.94	0.53	59.57	27.11	28.28	11.85	38.46	18.66	8.56	56.66	18.76	15.93	18.86
8.	0.66	0.30	-	-	8.19	0.07	-	1.75	53.13	5.26	0.68	38.46	34.68	66.09	6.67	45.84	35.71	17.50
9.	0.22	-	-	-	0.34	-	-	0.17	3.91	-	0.17	-	17.64	20.20	-	19.30	9.06	4.18
10.	-	-	-	-	-	-	-	-	0.15	-	-	1.53	5.07	0.51	-	3.48	0.27	0.65
11.	-	-	-	-	-	-	-	-	-	0.65	-	-	0.60	-	-	0.53	-	0.10
12.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15.	203	159	292	236	137	590	93	273	307	74	285	30	229	281	43	178	165	243
16.	6.72	6.37	6.75	5.65	8.19	7.33	6.74	9.31	6.85	8.70	7.52	11.72	14.34	15.59	13.38	15.03	11.71	10.75
17.	7.16	6.64	6.98	5.78	9.18	7.51	6.91	9.66	13.70	9.06	7.89	13.03	17.10	16.44	14.23	17.11	13.52	11.28
18.	0.04	0.02	0.05	0.02	0.05	0.13	0.02	0.13	0.41	0.03	0.07	0.03	0.60	0.65	0.07	0.47	0.21	0.20
19.	10.7	8.5	7.9	6.3	11.7	9.5	7.2	11.7	18.2	-	11.0	15.9	26.9	27.5	17.4	25.7	16.2	14.3
20.	3.1	5.6	7.1	7.7	4.9	3.7	14.3	7.4	5.3	-	5.4	6.1	2.7	4.9	6.5	4.7	5.4	6.0
21.	-	base	centre	edge	centre	centre	edge	centre	edge	edge	centre	top	centre	top edge	edge	edge	centre	-
22.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	slight	-
23.	-	-	-	-	-	100	-	100	100	-	100	-	-	-	-	100	20	-
24.	wispy	-	-	-	-	-	-	-	-	-	-	wispy	-	-	-	-	-	-

Table 4
Flight 9. 24/9/51

Item no.	117.	118.	119.	120.	121.	122.	123.	124.	125.	126.	127.	128.	Mean values
1.													
2.	3,460	4,450	4,580	5,450	5,500	6,400	7,420	7,460	7,470	8,430	8,430	8,450	-
3.	-	-	-	-	-	-	-	-	-	-	-	-	-
4.	431	213	305	143	289	175	192	89	242	303	253	195	-
5.	5.8	14.0	19.3	20.3	34.6	21.7	4.7	14.6	19.0	14.8	28.5	10.2	17.3
6.	10.6	22.5	28.9	21.0	20.1	13.7	9.4	16.8	13.2	18.5	15.4	10.3	16.7
7.	16.2	26.8	12.2	8.4	9.3	12.6	7.3	11.2	13.2	14.5	11.1	11.3	12.8
8.	44.0	14.1	18.4	18.9	14.9	26.9	43.2	9.0	9.5	11.5	8.7	29.7	20.7
9.	17.4	9.4	5.6	21.7	4.8	18.3	26.0	29.2	16.5	7.6	5.5	21.5	15.3
10.	3.9	4.7	2.3	9.1	2.4	6.9	8.9	15.7	23.1	5.6	5.9	15.9	8.7
11.	0.7	6.6	3.9	0.7	5.2	-	-	2.2	3.7	8.6	5.5	1.0	3.2
12.	0.2	1.9	7.8	-	6.6	-	0.5	1.1	0.8	14.5	14.6	-	4.0
13.	0.5	-	1.3	-	1.7	-	-	-	0.8	4.3	4.7	-	1.1
14.	0.2	-	0.3	-	0.4	-	-	-	-	-	-	-	0.1
15.	198	99	140	64	129	80	91	41	121	142	118	95	110
16.	15.39	14.63	16.93	13.99	16.27	13.46	16.70	17.12	11.82	24.62	23.14	16.73	16.73
17.	22.98	22.88	32.72	18.10	32.96	16.82	18.67	22.68	26.16	40.34	40.41	20.26	24.88
18.	1.26	0.62	2.57	0.20	2.40	0.20	0.36	0.25	1.22	4.86	4.08	0.41	1.54
19.	-	50.1	85.1	29.5	100.0	26.3	27.5	38.0	52.5	-	-	29.5	48.7
20.	-	2.6	2.8	4.2	2.38	3.7	5.0	3.39	3.2	-	-	4.3	3.5
21.	edge	centre	centre	centre	centre	edge	centre	edge	centre	centre	centre	top edge	-
22.	heavy	slight	mod.	mod.	mod.	mod.	mod.	-	heavy	mod.	mod.	-	-
23.	100	100	300	50	-	-	20	100	150	100	100	100	-
24.	-	thin	thin	-	-	-	-	wispy	-	-	-	-	-

Flight 10. 26/9/51

Item no.	129.	130.	131.
1.			
2.	3,900	3,950	3,970
3.	46.0	46.0	47.0
4.	235	454	773
5.	2.1	3.3	1.5
6.	18.7	10.1	3.2
7.	18.7	29.5	8.5
8.	48.5	52.6	69.2
9.	12.0	4.4	15.9
10.	-	-	1.4
11.	-	-	0.1
12.	-	-	-
13.	-	-	-
14.	-	-	-
15.	106	205	404
16.	13.26	12.82	15.44
17.	14.55	13.15	16.47
18.	0.17	0.24	0.94
19.	17.8	22.9	22.9
20.	6.7	5.3	3.5
21.	-	-	base
22.	-	-	-
23.	100	200	-
24.	wispy	wispy	wispy

Table 4
Flight 10 (contd.)

Item no.																	
1.	132.	133.	134.	135.	136.	137.	138.	139.	140.	141.	142.	143.	144.	145.	146.	147.	148.
2.	4,850	4,850	4,900	5,900	5,900	5,900	5,900	6,600	6,800	6,850	6,900	6,900	6,900	7,800	7,800	8,750	8,800
3.	43.0	43.0	44.0	40.0	39.0	41.0	38.0	35.0	35.0	35.0	35.0	36.0	33.0	33.0	32.0	29.0	29.0
4.	542	409	145	817	582	237	510	423	372	420	463	188	587	205	452	461	272
5.	6.8	2.2	15.8	0.4	0.7	-	17.2	6.1	10.7	14.0	2.2	34.0	8.6	12.2	8.2	32.1	14.0
6.	12.4	5.1	34.5	3.9	7.2	16.4	32.0	13.9	13.4	26.2	7.5	31.9	8.4	15.6	20.0	36.5	11.0
7.	23.2	8.8	18.0	47.3	7.0	20.2	11.2	9.2	13.2	12.6	16.2	22.3	7.7	9.3	31.8	11.0	15.8
8.	27.2	31.8	21.4	45.7	17.5	27.5	19.2	40.2	30.1	32.6	37.1	6.9	50.9	7.8	32.0	10.2	30.5
9.	16.8	18.4	5.5	0.6	52.0	31.6	10.2	28.4	22.3	10.2	30.7	4.8	23.2	10.2	6.2	3.7	14.7
10.	11.8	27.2	3.4	1.6	10.3	3.4	7.8	1.2	6.7	3.2	3.9	-	1.2	13.2	0.9	3.2	9.9
11.	1.5	5.9	1.4	0.5	3.4	0.8	2.2	0.9	2.7	1.2	2.1	-	-	10.7	0.4	1.5	2.9
12.	0.2	0.4	-	-	1.5	-	0.2	-	0.5	-	0.2	-	-	15.1	0.2	1.5	0.7
13.	-	-	-	-	0.2	-	-	-	0.3	-	-	-	-	4.4	0.2	-	0.4
14.	-	0.2	-	-	-	-	-	-	-	-	-	-	-	1.5	-	-	-
15.	258	195	70	414	285	106	225	196	182	204	233	86	285	99	219	235	119
16.	15.65	21.27	11.27	12.79	20.67	15.57	12.89	15.16	15.91	12.51	16.68	8.56	14.81	29.08	12.13	10.43	15.88
17.	19.61	25.25	15.30	14.19	24.90	18.01	18.23	15.99	21.51	15.16	19.64	10.43	16.42	45.77	16.49	18.45	24.42
18.	1.02	1.64	0.13	0.62	2.30	0.33	0.71	0.55	0.95	0.43	0.92	0.06	0.66	4.98	0.51	0.77	0.70
19.	40.7	36.3	-	-	-	28.8	40.7	28.8	-	25.7	-	17.8	19.9	61.7	-	70.8	-
20.	3.2	3.8	-	-	-	3.6	2.8	4.6	-	3.8	-	2.9	5.7	3.3	-	1.8	-
21.	edge	centre	centre	centre	centre	edge	centre	edge	edge	edge	-	edge	edge	centre	edge	edge	centre
22.	-	-	-	-	-	-	-	slight	-	slight	-	-	-	-	-	-	-
23.	-	5	50	5	100	100	50	100	200	20	300	10	50	5	50	500	10
24.	wispy	-	-	-	dense	-	-	-	-	-	wispy	-	-	-	-	-	-

Table 4
Flight 10 (contd.)

Item no.			Mean values
1.	149.	150.	
2.	8,800	8,850	-
3.	30.0	29.0	-
4.	377	485	-
5.	14.6	2.1	9.49
6.	10.9	5.2	15.64
7.	7.9	3.9	16.01
8.	26.5	23.3	31.30
9.	38.5	54.1	18.84
10.	1.6	10.7	5.57
11.	-	0.6	1.76
12.	-	-	0.93
13.	-	-	0.25
14.	-	-	0.01
15.	173	217	205
16.	15.08	19.46	18.81
17.	17.36	21.09	19.19
18.	0.47	1.08	0.81
19.	36.3	19.1	32.0
20.	3.3	6.1	4.1
21.	edge	centre	-
22.	-	-	-
23.	10	10	-
24.	-	-	-

A note on M.R.P. 991

by

B.C.V. Oddie (Meteorological Office)

The relationship between drop-size distribution and visibility

The visibility can be calculated from a known droplet-size distribution by means of the equation

$$\frac{15.6}{\pi V} = \sum_i K_i n_i d_i^2$$

where V is the visibility, and n_i is the number of droplets of diameter d_i per unit volume. The value of K_i is somewhat uncertain: it is believed to vary between 1 and 2, and is here taken to be 2: but there is some reason to think that a variable and somewhat lower value might be appropriate (see e.g. Johnson 'Physical Meteorology' pp. 81-83).

The visibility has been calculated in this way from all those measurements of drop-size distribution in M.R.P. 991 for which estimates of visibility were made. The results are shown in Table I. On an average of 59 cases, the calculated visibility was 98 yd., the measured visibility 96 yd. This very close agreement is undoubtedly to some extent fortuitous: but it confirms, in a general way, that the sampling technique is sound - that no class of drop which is significant in the visibility problem is escaping detection, and that the drop-sizes are fairly accurately estimated.

It follows that the estimates of water content must be fairly reliable: for if this sampling technique misses any class of drops, it must be the smallest ones. If the effect of the missed drops on visibility is, as we have seen, not very great, the effect on water content must be even less, since the former is proportional to $\Sigma n_i d_i^2$, the latter to $\Sigma n_i d_i^3$.

When one comes to examine the individual observations, the agreement is much less good. This was to be expected. In the first place, estimates of visibility made from an aircraft in cloud are highly subjective, since the most distant object which can be seen is the wing-tip, 50 feet or so away. Again the almost instantaneous sample of droplets is not necessarily a representative one; this is especially true in cumulus cloud which is always patchy.

Apart from the wide general scatter, the most striking and consistent feature of Table I is that at very low observed visibilities (25 yd. or less) the calculated visibility is always greater than the observed, by a factor of about 5. This ratio is relatively constant: except for one case, (where the value is 60) all the values lie between 3 and 7.2.

A discrepancy at these low visibilities is the more remarkable because it is precisely in this range that the direct observations of visibility should be most reliable. No satisfactory explanation can be offered.

It is suggested that work on the relationship between visibility and drop-size distribution in cloud should continue in an attempt to trace the reason for the discrepancies in Table I. The great disadvantage of the sampling technique is the enormous labour of counting and sizing droplets: but so long as our interest is limited to visibility, neither operation is necessary - we merely need to know the total area covered by the droplets on each slide, and it should be possible to estimate or measure this by a single operation. An accurate means of measuring visibility is also necessary.

G.3178/AG/6/56/50

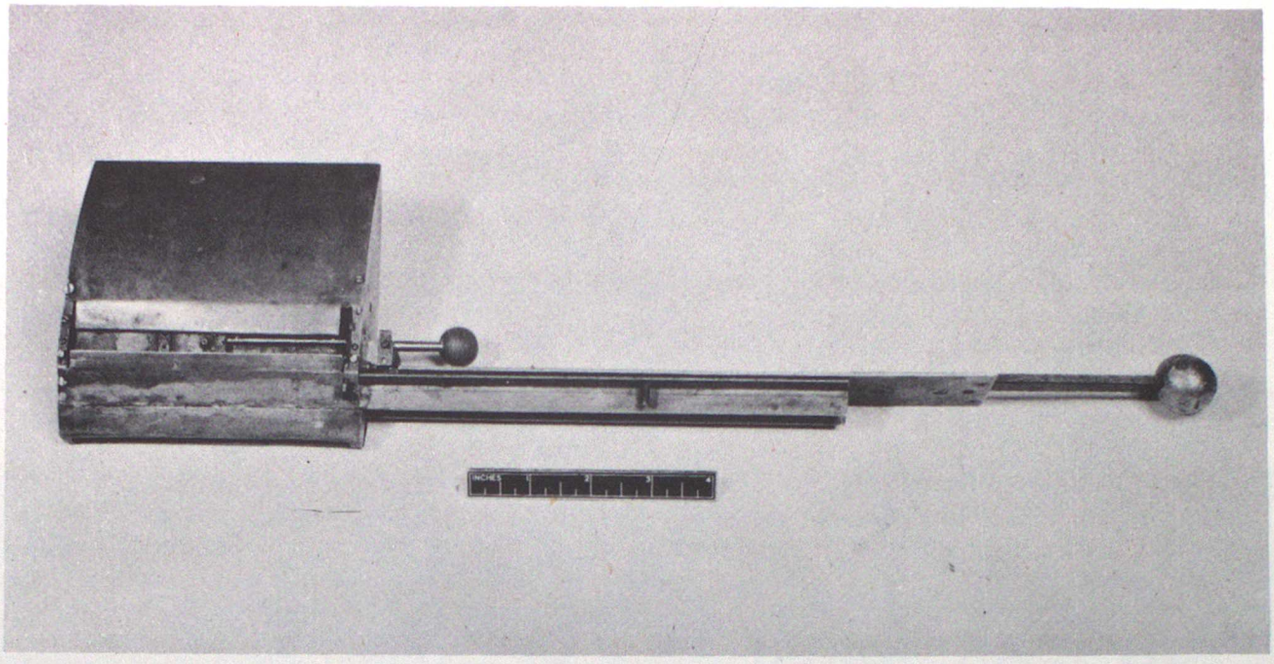
Table I

Visibilities calculated from the measured drop-size distribution of M.R.P.991 compared with estimated visibilities

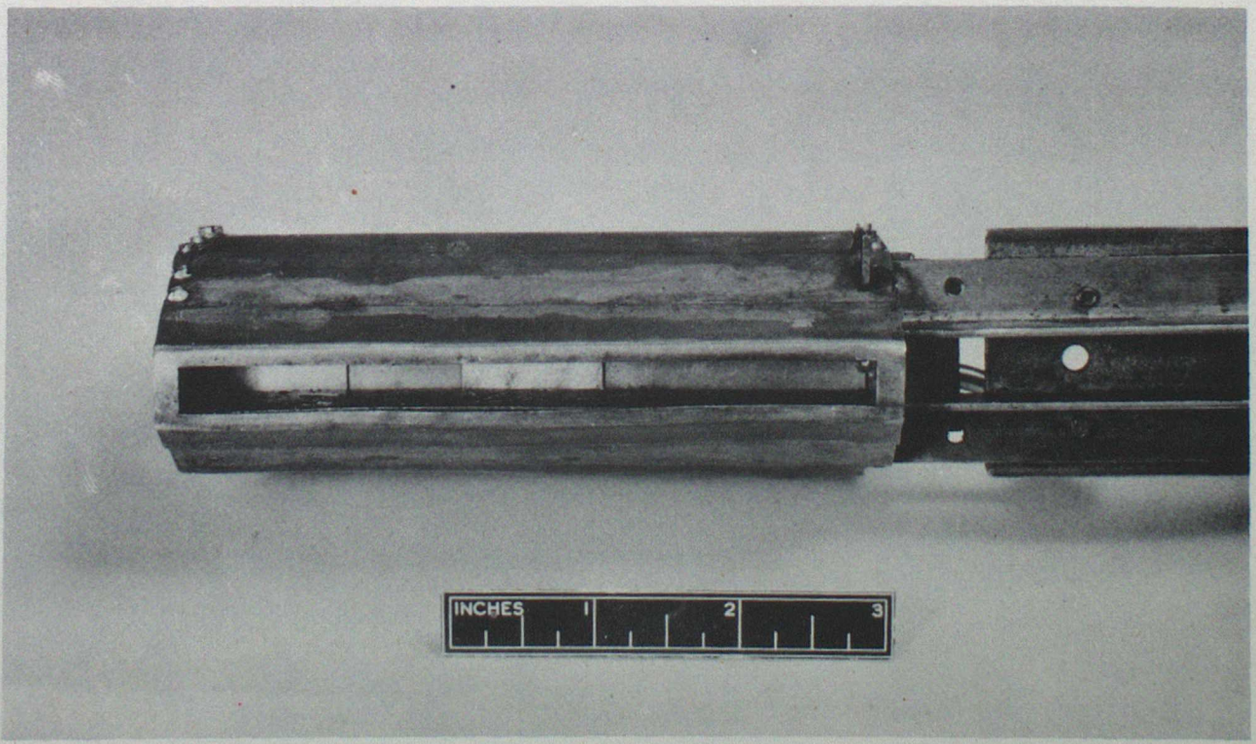
Observation number	Estimated visibility (yd.)	Calculated visibility (yd.)	Observation number	Estimated visibility (yd.)	Calculated visibility (yd.)
13	< 20	78	118	100	79
14	< 20	68	119	300	42
15	< 10	36	120	50	160
16	< 10	45	123	20	92
41	100	88	124	100	170
58	100	103	125	150	47
59	100	52	126	100	17
60	50	59	127	100	20
61	50	58	128	100	82
62	50	40	129	100	130
63	50	36	130	200	76
64	50	45	133	5	26
65	50	79	134	50	220
71	100	290	135	5	36
83	100	112	136	100	19
86	200	450	137	100	92
87	200	270	138	50	48
89	200	97	139	100	52
90	200	98	140	200	49
92	200	130	141	20	66
94	100	250	142	300	36
95	100	49	143	10	600
96	100	140	144	50	39
105	100	83	145	5	19
107	100	101	146	50	67
108	100	51	147	500	61
110	100	160	148	10	64
115	100	60	149	10	59
116	20	104	150	10	30
117	100	43			
			Mean	96	98

M.R.P. 991

FIG. I. PHOTOGRAPHS OF CLOUD DROPLET SAMPLER.



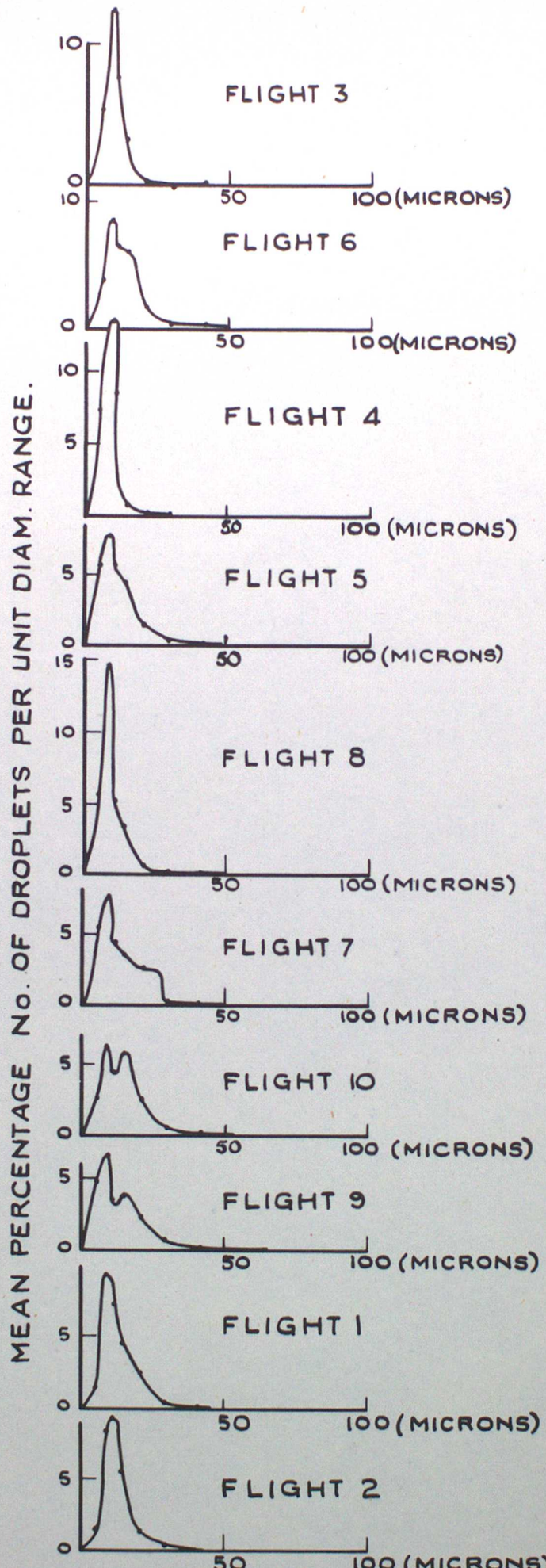
(a) View of complete instrument.



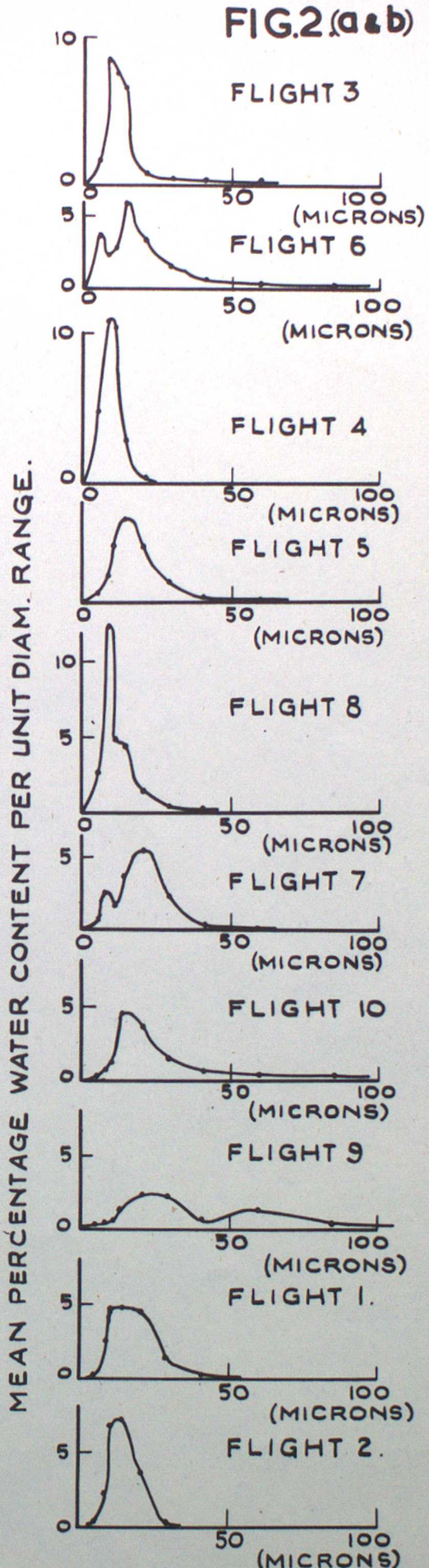
(b) Close-up view of shutter arrangement.

M.R.P. 991

FIG.2 (a & b)

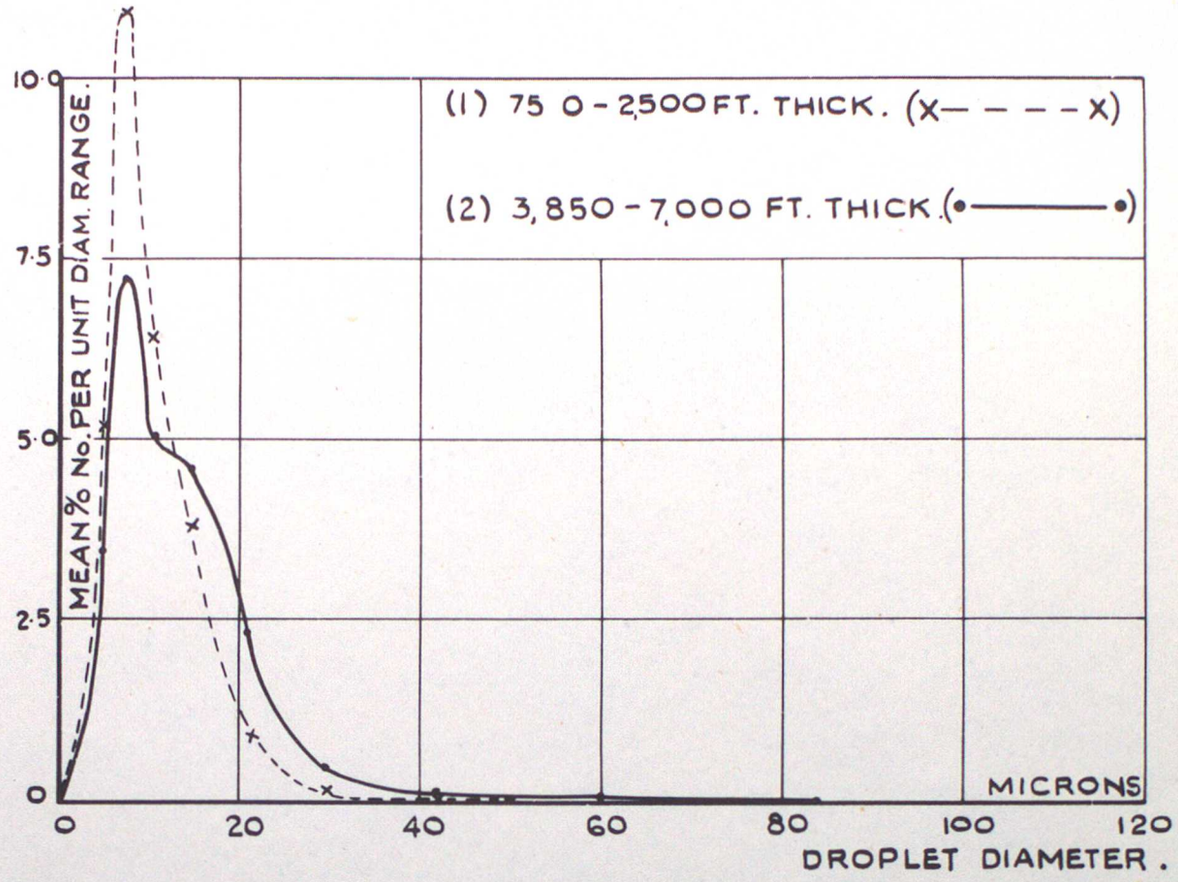


(a) SIZE – NUMBER SPECTRA.

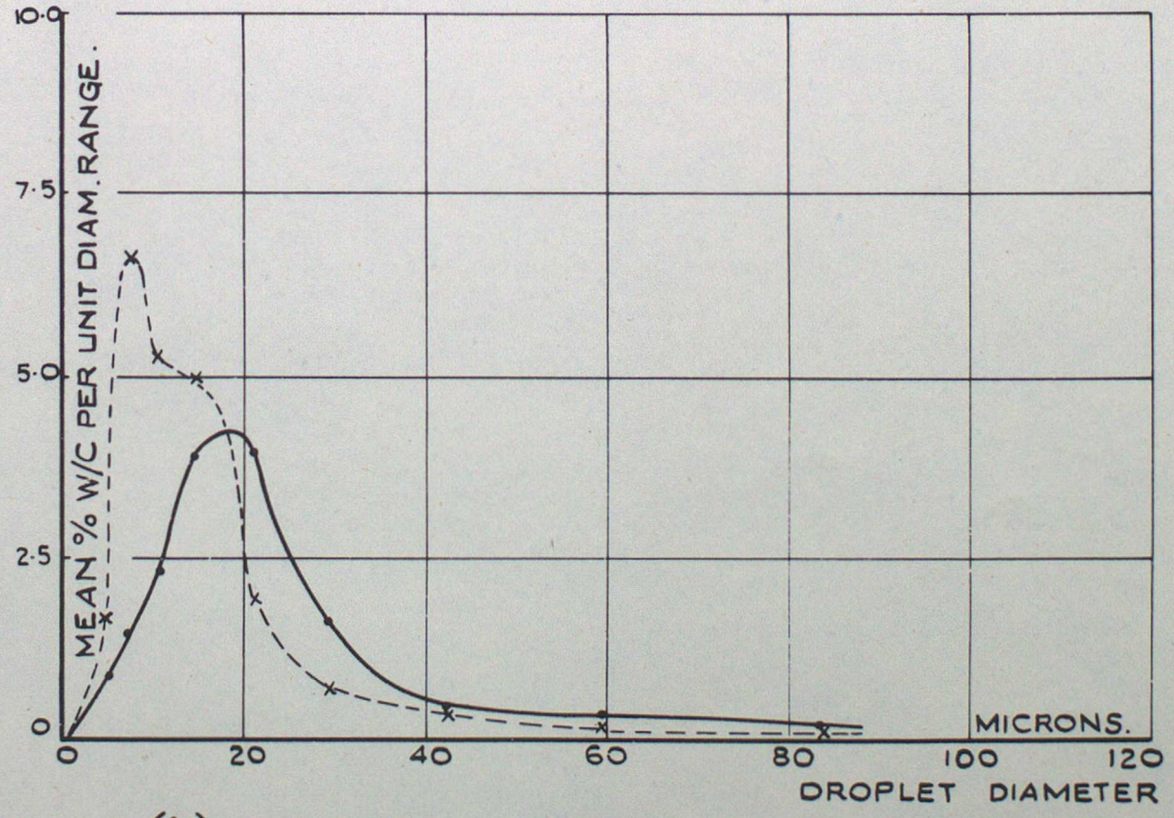


(b) SIZE – WATER CONTENT SPECTRA.

FIG. 2. (a & b)



(a) NUMBERS OF DROPLETS.



(b) WATER CONTENT.

FIG.3.(a & b) COMPARISON OF WEIGHTED MEANS BETWEEN TWO GROUPS OF FIVE CUMULUS CLOUDS.

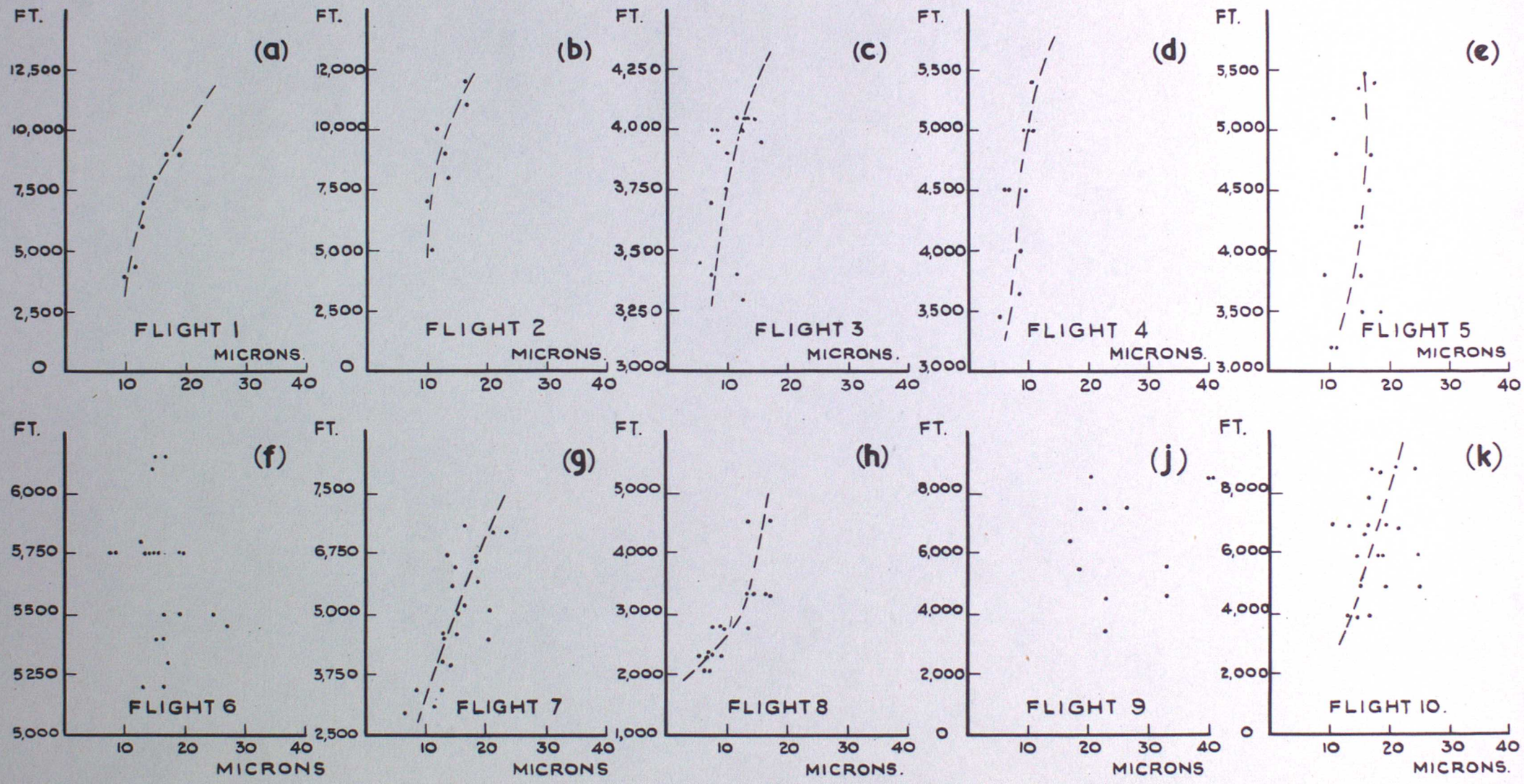


FIG.4(a-k) VARIATION OF MEAN VOLUME DIAMETERS WITH HEIGHT ABOVE GROUND.

M.R.P. 991
FIG.4(a-k)

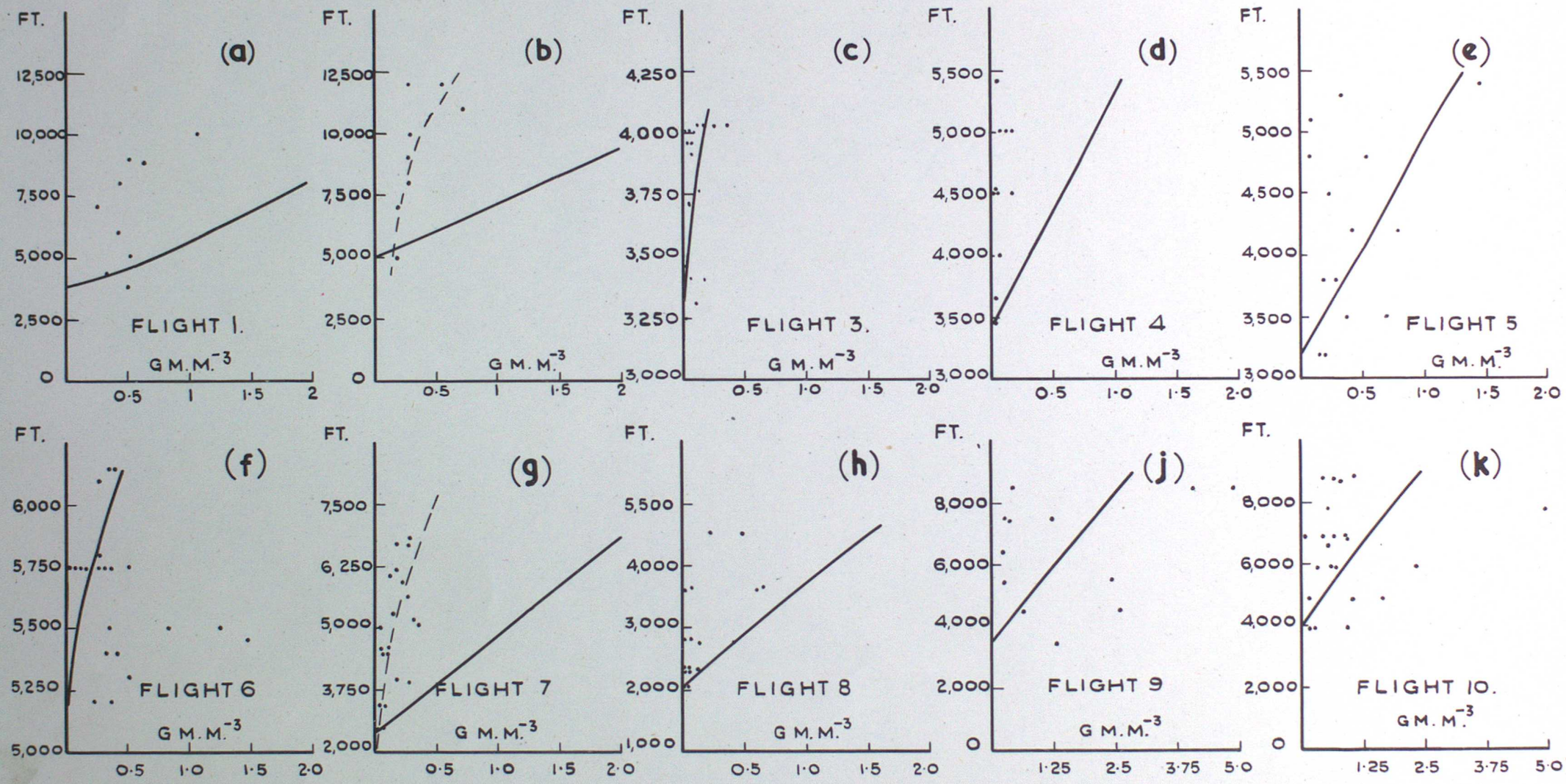


FIG.5(a-k) VARIATION OF WATER CONTENT WITH HEIGHT ABOVE GROUND.

(THE FULL LINE CURVES REPRESENT THEORETICALLY COMPUTED ADIABATIC VALUES.)

M.R.P.991
FIG.5(a-k)

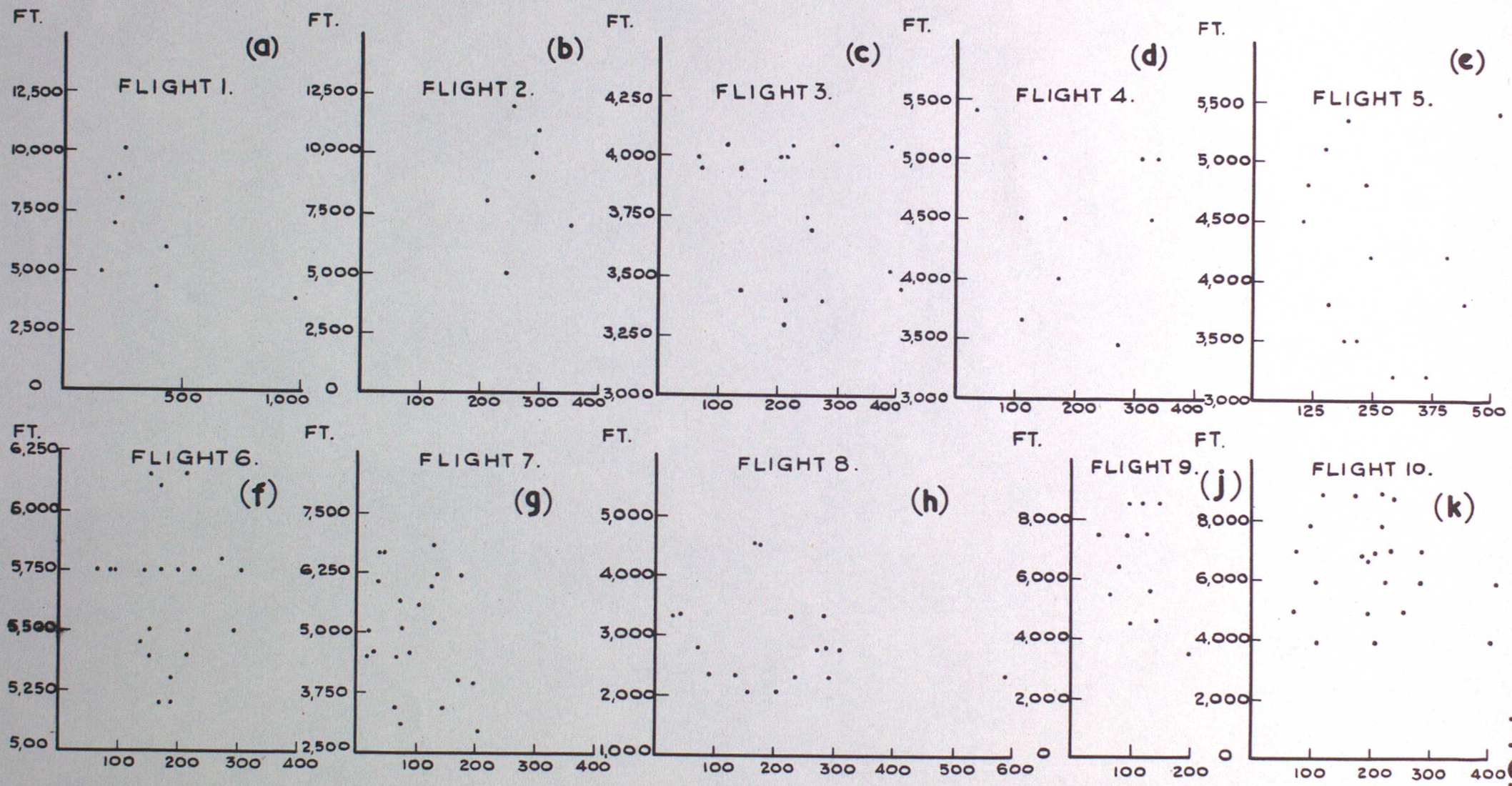
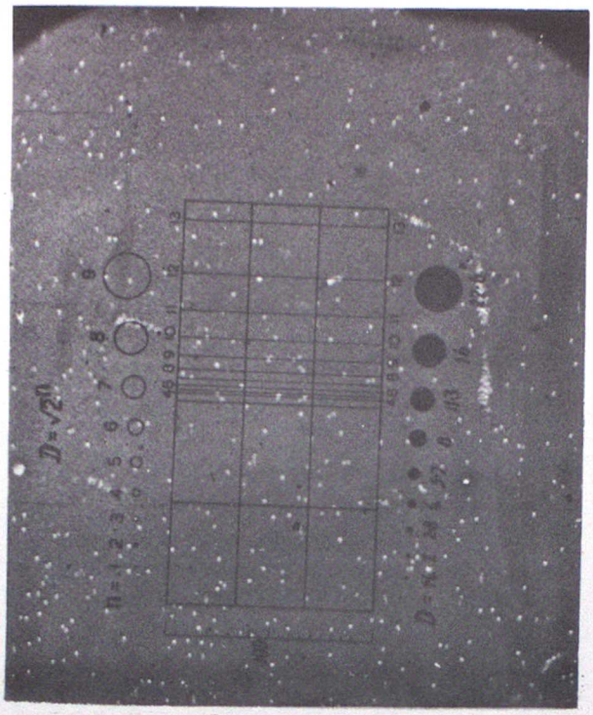
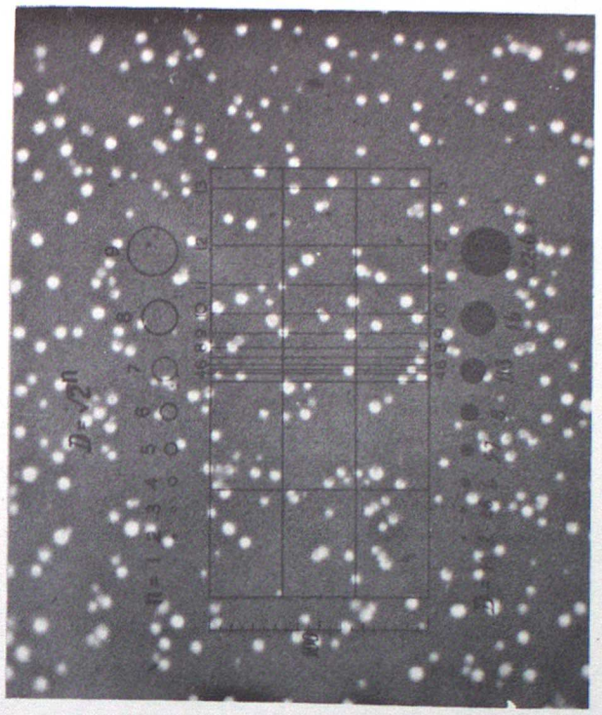


FIG.6(a-k) VARIATION OF NUMBER OF DROPLETS PER C.C. WITH HEIGHT ABOVE GROUND.

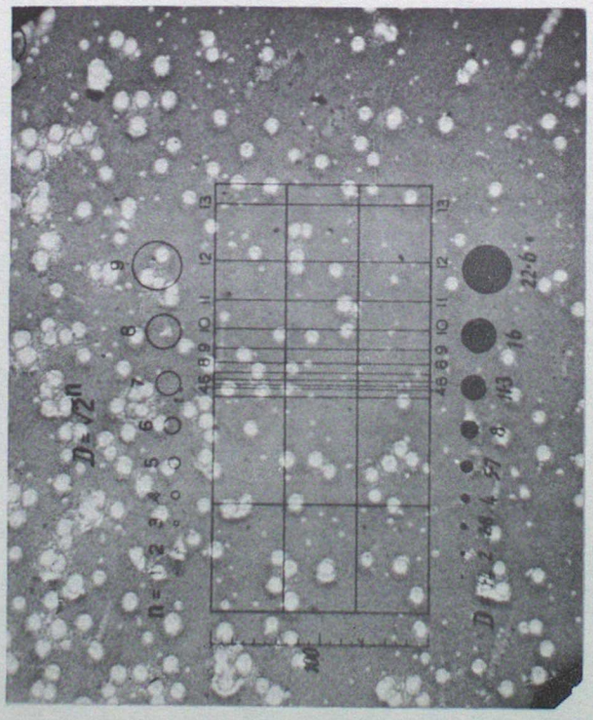
M.R.P. 991
FIG.6(a-k)



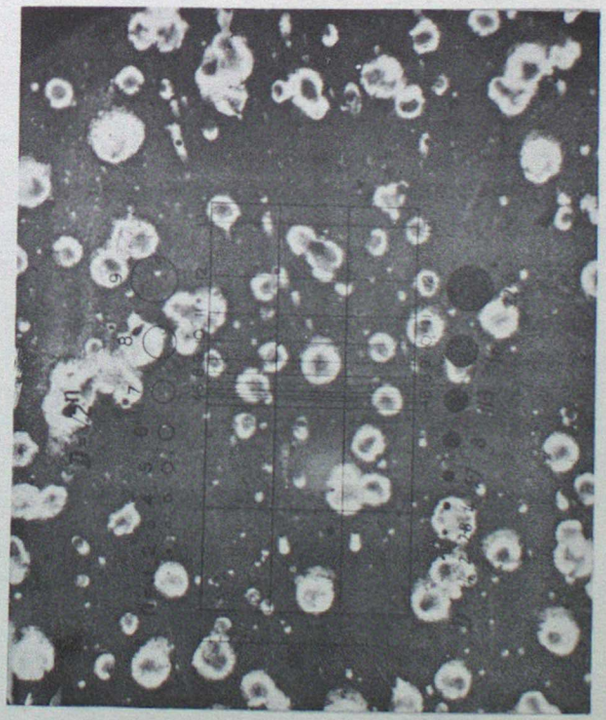
SAMPLE NO.100.
Mean volume diameter 7·16 microns
No of droplets per c.c. 203
Water content 0.04 gm.m^{-3}



SAMPLE NO. 2.
Mean volume diameter 11.62 microns
No. of droplets per c.c. 397
Water content 0.33 gm.m^{-3}



SAMPLE NO. 9
Mean volume diameter 20.1 m.crons
No. of droplets per c.c. 252
Water content 1.07 gm.m^{-3}



SAMPLE NO. 126
Mean volume diameter 40.34 microns
No. of droplets per c.c. 142
Water content 4.86 gm.m^{-3}

FIG. 7. SOME CLOUD DROPLET SAMPLES.

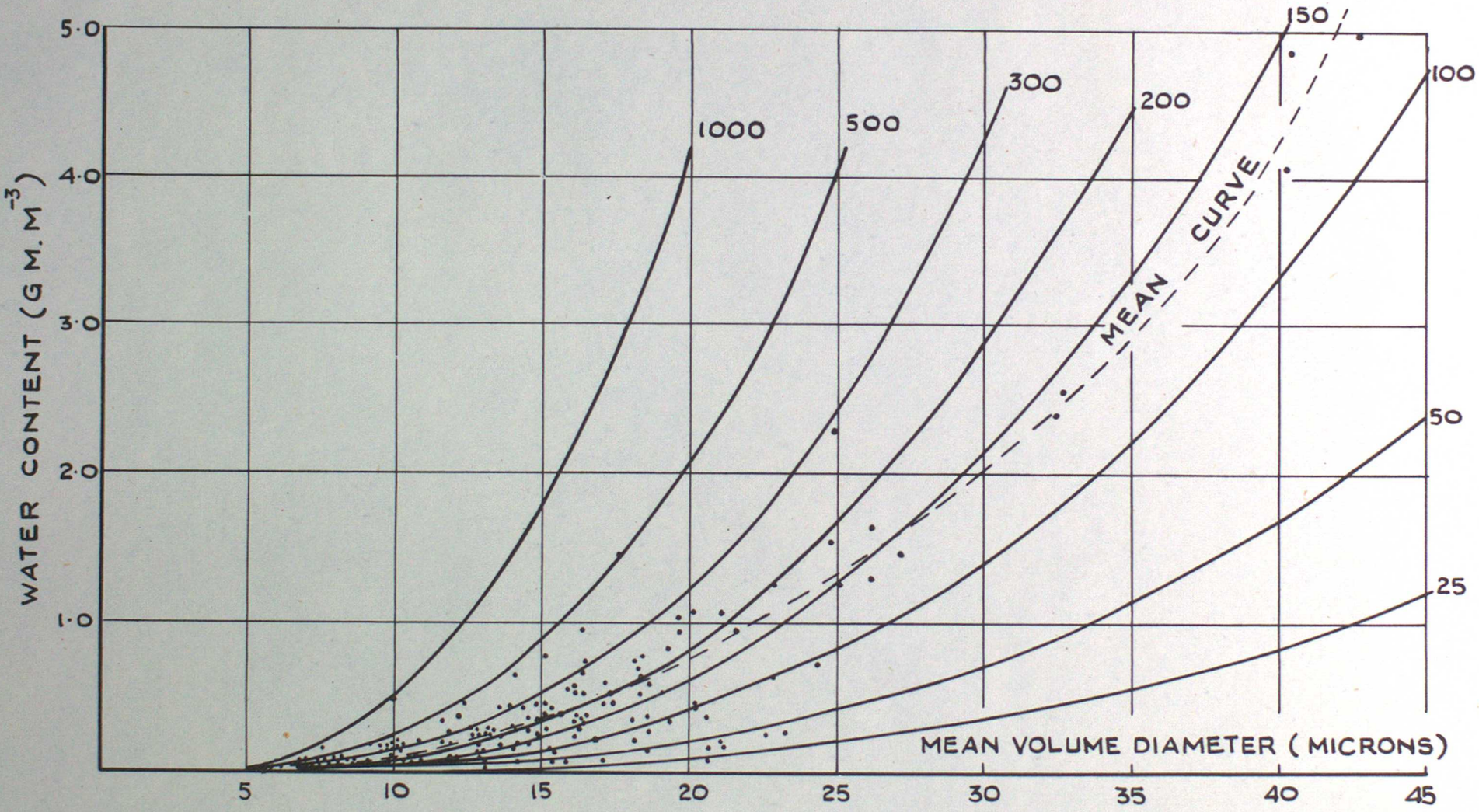


FIG.8. RELATIONSHIP BETWEEN WATER CONTENT, MEAN VOLUME DIAMETER & NUMBER OF DROPLETS PER C.C.

M.R.P.991
FIG.8

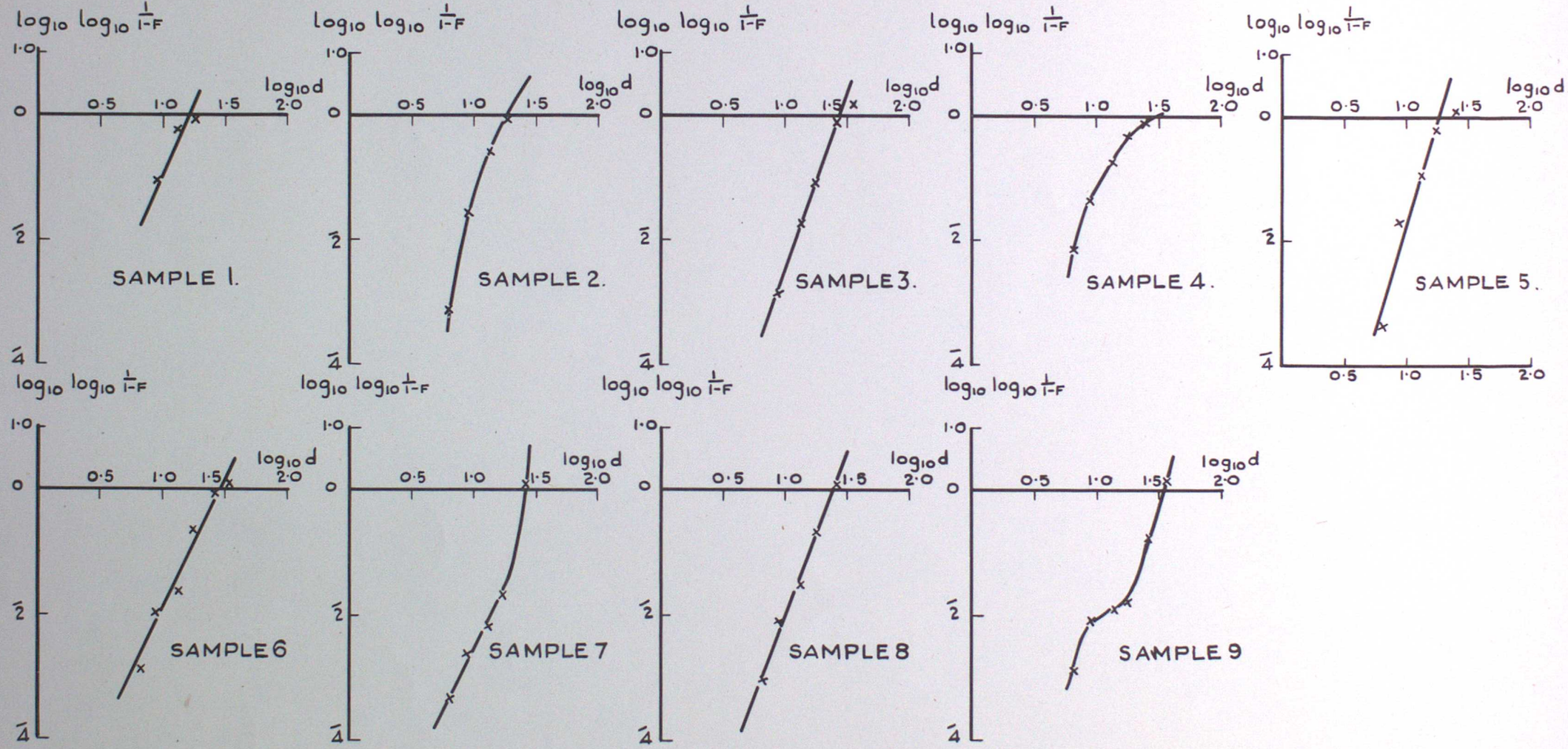


FIG.9. GRAPHICAL ILLUSTRATION OF THE NUMBER-DISTRIBUTION FORMULA $1-F=e^{-(d/a)^n}$ USING THE SAMPLES TAKEN ON FLIGHT 1.

M.R.P. 991
FIG. 9.

FIG.10(a - d)

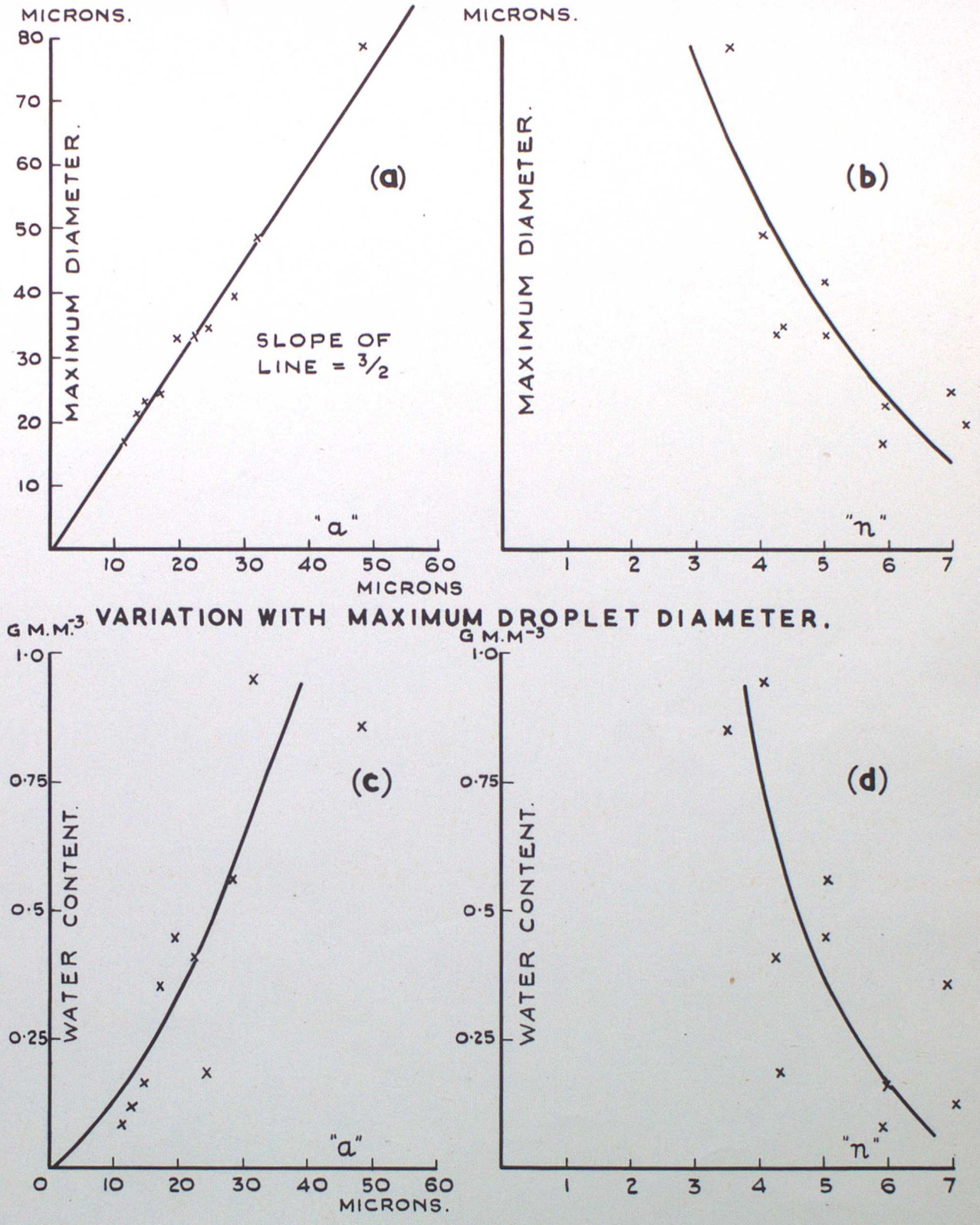


FIG.10(a - d) VARIATIONS OF BEST'S PARAMETERS "a" & "n" WITH MEAN VALUES OF MAXIMUM DROPLET DIAMETER & WATER CONTENT FOR THE TEN FLIGHTS.

(VALUES OF "a" & "n" WERE OBTAINED FROM 108 SAMPLES.)